A Method for Evaluating Air Carrier Operational Strategies and Forecasting Air Traffic with Flight Delay

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Airline Business Strategy and Operation Concept

BUSINESS STRATEGY

The commercial air transport industry came to life in the early 1920s and early air transport companies were mostly set up by pioneers and entrepreneurs. While passenger transportation was for a daring few, their main business was to deliver mail for the U.S. Post Office. With the advent of DC-3 aircraft in 1935, the economy and comfort of air travel was drastically improved, and air travel became a common means of transportation. Until the enactment of the Airline Deregulation Act in 1978, airlines were regulated so that the establishment of new market or the change of fare had to be approved by the Civil Aeronautics Board (CAB) or its predecessors. Under this rigid business environment, the market shares of the airlines were essentially fixed and they competed mostly on the basis of service [1,2,8].

After deregulation, airlines began to enjoy the freedom to schedule flights in any market at any price.[1] The external force of industry stability was permanently removed. With such freedom, airlines adopted new business strategies:

1. *Hub-and-spoke operation*. This strategy can be summarized as making all flights connect to a few hub cities. While travelers have to stop at the hub cities if they go from one spoke city to another spoke city, the possible markets that can be served from this system are vastly increased compared with point-to-point operations. Hub-and-spoke also has made it possible for the airlines to provide service even when the demand is so low that it would not be economically viable under point-to-point operations.

2. *Selling the right ticket to the right person at the right time*. This is done through the implementation of the so-called yield or revenue management system (YMS or RMS). The airlines exploit passengers' time value or time sensitivity of a ticket, which is a perishable commodity. The airlines sell tickets with different restrictions, designated by different fare classes, and control their availability based on the demand forecast. In practicing yield management, the airlines reserve some seats with higher prices for business travelers who tend to book a ticket with short advance notice. The airlines try to keep the optimal balance to reserve enough seats for the

[1] Due to congressional legislation, the following airports are slot-controlled: JFK, LGA, ORD, DCA. A slot -- a departure or an arrival at a certain time -- must be first be obtained by an airline before scheduling service at those airports. Except at less economic times when there is not much travel demand, all available slots have been taken.

higher-paying customers while not wasting a seat. A symbiosis is formed: business travelers subsidize leisure travelers while the leisure travelers fill the planes, which induces higher demand that leads to higher service frequency that business travelers demand.

3. *Cost reduction*. This is oriented toward service reduction, geared to providing minimal service to leisure travelers, which are now a major portion of passengers since deregulation. Various methods have been devised to reduce the cost through peanut fares, no baggage handling, no seat assignment, salary and wage reductions and two-tier wages, etc. Most start-up airlines embraced cost reduction as the centerpiece of their business strategy [2].

4. *Pursuit of growth*. This is done through the expansion of fleets, merger, and acquisition.

The landscape of the U.S. air transportation industry underwent a drastic shake-up after deregulation. Braniff, Eastern, and PanAm Airlines, household names associated with the early U.S. air travel industry, have disappeared. Northwest Airlines acquired Republic Air, while US Airways acquired Piedmont Airlines. People Express, the surging start-up, low-cost carrier, appeared on the scene, but could not manage the expansion, and finally went bankrupt. A new, promising, low-cost startup airline in the early 1990s, ValuJet, attempting to shortcut maintenance costs by using outside contractors, suffered an air disaster, merged itself with AirTran, and settled on an oblivious market position. The only low-cost airline with sustained growth to challenge the major airlines is Southwest Airlines, whose success is attributable to its aggressive strategy of tapping the under-served market with affordable prices.

With the arrival of new aircraft ordered years ago when air traffic was on the up trend, aggravated by the reduction of travel demand resulting from the Persian Gulf War and the subsequent economic recession, the airlines collectively faced the problem of over-capacity at the beginning of the 1990s. From 1990 to 1994, airlines collectively lost more money than they had made during all the years before 1990. Continental, TWA, and America West survived their economic crises through bankruptcy protection. United Airlines survived its hardship through an employee ownership plan, where employees opted for salary and wage reductions in exchange for 55 percent of the company. American Airlines is the only major domestic air carrier that did not lose money during that period; the major reason that it did relatively well is due to its deployment of information technology, such as yield management [27].

The most prominent business strategy embraced by all airlines during the early 1990s was to emphasize cost reduction. Continental started CaLite, a subsidiary with more than 100 daily operations at its hub at High Point/Greensboro Airport, North Carolina. Delta Airlines, the southern airline traditionally superior in service, announced the so-called 7.5 plan—a plan to reduce the cost per available seat mile (ASM) from 12 cents to 7.5 cents by year 2000. US Airways eliminated first class seats in some aircraft in order to put in more coach seats, thus reducing their cost per ASM flown.

Since 1995, blessed by strong business travel demand induced by the booming economy, the airlines have ridden the economic tail wind to prosperity with record profits. A new generation of executives also has replaced the last generation: with the exception of Southwest Airlines, all the major airlines have installed new chief executive officers (CEOs) during the past few years. The airlines, learning from their folly in the 1980s and early 1990s, have embraced *rationality* in their decision-making: instead of pursuing growth for the sake of growth, they now emphasize maximizing shareholder value as measured by return on equity (ROE) or return on investment (ROI) [16]. The embrace of rationality has certainly reduced the uncertainty in predicting airline behaviors.

With shareholder value in mind, the airlines seem to follow a general script to design their business strategy [3]. Broadly speaking, the airlines are trying to find ways to enhance revenue, reduce cost, and improve their competitive stance, summarized as follows:

1. *Schedule optimization*. The airlines continue to fine-tune their schedules. Among the schedules operated by the major carriers, the hub-and-spoke operations are even more intensified. Continental's decision to reduce operations at Denver and Greensboro/High Point and to increase operations at its hubs at Houston and Newark testify to this phenomenon [4,5]. US Airways' decision to withdraw from some small, unprofitable markets and to reduce its fleet also reflects the airline's resolve to put shareholder value first. However, we have also witnessed the growth of some small markets by the low-cost carriers, like Providence, RI, and Long Beach, NY, which were recently picked up by Southwest Airlines.

2. *Cost reduction*. This is achieved, not by the reduction of service but by the consolidation of fleet, exclusive purchase deals from aircraft manufacturers, reduction of travel agencies' sales commissions, and service outsourcing. By consolidating their fleets to just a few aircraft types or to the same manufacturer, airlines can benefit from the reduced spare part inventory and reduced air crew training. The purchase of all the narrow body as well as wide body aircraft from Airbus Industrie by US Airways reflects this thinking. Using just Boeing 737 aircraft in Southwest's fleet is one of the carrier's ways to keep cost low. Signing exclusive purchasing deals with the aircraft manufacturers, although with different aircraft types, is a way to reduce the equipment cost since the manufacturers can enjoy the economy of scale and certainty of production planning and, thus, can pass the benefits to the airlines. Outsourcing services traditionally performed by the airline, such as maintenance and reservations, has become more and more popular. In so doing, airlines can concentrate on what they do best — serving their flying customers. US Airways has even contracted

with Saber Decision Technology (SDT) to manage its information technology (IT) department.

3. *Building brand name*. This is perhaps most important to attract business and frequent travelers, who contribute the most revenue and profit to the major airlines. While airlines are still using frequent flier miles bonuses and club facilities to segregate the market and to keep and reward their loyal frequent customers, they are also improving service including the upgrade of club facilities at airports, installation of electronic equipment like telephones and facsimiles to aircraft, and most importantly by keeping their schedules punctual. To help attract business travelers, who care most about punctuality, airlines pay particular attention to the on-time performance statistics published by the Department of Transportation (DOT).[2] In order to improve their on-time statistics, US Airways formed special employee task forces, and employees at Continental Airlines get a bonus if on-time performance targets were met. Most of the flight delays are caused by the improper internal procedures or disorganization under airlines' control.

4. *Alliance*. This typically takes the form of recognition of partners' frequent flier programs, code sharing, and joint schedule development. Code sharing enables a seamless travel experience for passengers between partner airlines; the passengers do not need to change airlines, or check baggage at the connection point, as if they were served by one airline. When making reservations, both airlines' services will appear on the computer reservation system (CRS) for any partnered airline, which dramatically increases the markets that can be served by either partner. Code sharing is a win-win strategy for both partners because both get additional revenue at no additional cost. However, in a larger marketplace, alliance is a zero-sum game—the gain to the partnered airlines is at the expense to the airlines not in the alliance. Because of this, American Airlines, traditionally favoring internal growth and an arch opponent to airline alliances, finally has joined the ranks and formed One World Alliance.[3] Code sharing has traditionally been established between the major carriers and their affiliated commuters, wherein the commuters feed the traffic to the majors and the majors transport passengers to the destination that commuters could not. Now, alliance is played at the national and international marketplace among the major and flagship carriers. Alliance enables the airlines to avoid the antitrust statutes and the other legal hurdles regarding foreign ownership of airlines and to operate as one virtual airline.

5. *Use of information technology*. The airlines continue to embrace the operations research/management science (OR/MS) techniques to wring out more revenue and cost reduction by deploying the right resource to the

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[2] A flight is classified as *late* in DOT's Airlines Service Quality Performance (ASQP) database if its arrival is more than 14 minutes later than the schedule.

[3] One World Alliance now consists of American Airlines, British Airways, Quantas Airlines, Canadian Airlines, and Cathay Pacific Airways.

right place at the right time. The advent of the Internet offers airlines new ways to distribute their product—flight seats—to the public, through ticketless or Web booking.

OPERATION PRACTICE

There are basically three flows in the airline business: passenger, equipment, and crew. Being in the transportation business, airlines deploy their equipment and crew to serve the passengers. Since it is a complex business, airlines view their operations as comprising all the processes to move the flows including scheduling, crew assignment, staffing, ticketing and gate service, and baggage handling, etc. In this task, we are primarily interested in the operational process of moving aircraft.

To a traveling passenger, the flight experience is simply going to the airport and sitting in the aircraft for a few hours after handing over a ticket. But many people are behind the scenes to ensure that this brief journey in the air from one airport to another is on time and safe. The most salient feature of air transportation is the schedule of a flight, which the airlines are responsible for developing, and safety, which is the shared responsibility of airlines and the government through air traffic control.

Schedule Development

Since air transportation is expensive and demands a high load factor, and passenger demand is function of time of departure, time of arrival, and connection possibilities in a network, schedule development is crucial to an airline. In order to develop a schedule that permits efficient operation of flights, flight schedulers must take into account many factors such as airport structure, habitual adverse weather (such as predictable fog), crew time limits, air traffic control and routings, and ground service capacity. Its importance became even more apparent after 1978 when the air transport industry was deregulated, which allowed the airlines to schedule freely unless involved with the slot-controlled airports. Schedule development is typically done by performing the following steps:

1. *Market planning*. Through market research, the airlines assess the market demand and project the future growth of the market. Forecasting is used to attempt to quantify future demand in a certain market or markets for planning purposes. The scheduling department then uses this demand data to develop a schedule of flight operations. Also, schedulers must consider what the competition will do, the problem of traffic flow, the salability of a schedule to customers, and load-factor leverage. Since deregulation, all major airlines have adopted the hub-and-spoke operation as the cornerstone of their schedules.

2. *Fleet assignment*. Given fleet composition, the maintenance location, and regularly scheduled maintenance, the fleet schedule is assigned to maximize the expected revenue. This is a vehicle routing problem that connects the schedule given from market planning with desired equipment with the most efficiency. The solution to the fleet assignment problem is highly automated among the carriers by software run on powerful computers. The software packages used by the carriers are almost identical; differences among the packages lie mainly in their speed of execution and flexibility[6, 24].

3. *Crew assignment*. Given the fleet assignment, crew qualification (seniority and certifications) and their home base, crew schedules are generated with minimum crew cost while adhering to crew duty regulations and the pilot labor contract. Like the solution to the fleet assignment problem, the solution to crew assignment is also accomplished by using highly sophisticated, mixed integer programming mathematical models run on powerful computers. Like fleet assignment, crew assignment software is essentially a commodity, i.e., the models are similar across the carriers, and the differences lie mainly in computation speed and flexibility.

Some iterations between market planning and fleet assignment are needed mainly to satisfy station managers to ensure necessary staffing and service equipment. Market planning is the least understood of the schedule development steps, and the carriers do it using a hodgepodge of techniques.

One can see that delay is not explicit in the schedule planning process. However, this does not mean the management of a carrier does not pay attention to delay statistics. Apart from weather delays, most delays experienced by the airlines are caused by poor coordination, insufficient staffing, equipment breakdown, or inadequate procedures (such as those for passengers awaiting connecting flights).

Another reason that the carriers have not explicitly considered delays due to inadequate NAS capacity is simply that these delays have not yet become excessive. One major U.S. air carrier told us they tend to lengthen the block time for the flight at the end of the departure push to accommodate the ATC-induced delays. Pleas of carriers' operations departments to reduce the number of departure flights at rush hours have been overruled by their marketing departments because they can make money even with some delays.

Flight Plan and Filing

Flight plans are filed right before the takeoff of a flight. Most airline operations centers (AOCs) send a desired flight plan electronically to the en-route center host computers, while some air carriers file bulk-stored flight plans with each en-route center.

A flight plan is a profile of flight. The FAA's preferred routes had been the routes that airlines had to follow from one airport to another; now the airlines also can request different routes that will maximize flight efficiency. Although flight fuel consumption is considered by more sophisticated airlines when requesting the different routes, flight delays due to insufficient air traffic control are not considered.

Flight Operations

This covers the span of time that the real flight takes place from push-back at the departing airport to the gate at arrival airport. Although the equipment and technologies involved have been evolved, the procedures and the framework of ATC remained the same since the early 1960s as described in the following.

When a flight is ready to depart the pilot receives clearance delivery service via radio or PreDeparture Clearance (PDC) Program. The clearance delivered is as close as possible to the requested flight plan based on safety, current traffic flows, and directives. The PDC Program may only be used if the submitted flight plan is not amended. The ramp tower will direct the pilot through gate control, push back operations, and initial departure sequencing in the ramp area. Ramp towers are located mostly at major airports.

As the aircraft taxis to the departure queue, the pilot follows instructions from the ground controller in the airport tower. The local controller issues a take-off clearance when he deems it is safe, or, when take-off clearance cannot be issued because of traffic, authorizes the pilot to taxi into position and hold.

After the aircraft leaves the ground, the local controller informs the pilot to contact departure control. Once the departure controller has supervised the aircraft out of the TRACON departure area, the aircraft is handed off to the en-route sector controller. The en-route controller also directs the aircraft to avoid possible conflicts with other aircraft in the area, and may give guidance on weather or other variables in the system. . The aircraft is handed off from one en-route controller to another, as the flight progresses until the flight nears the arrival area. At this point the flight is passed off to the arrival TRACON controller, who provides guidance through the airspace, advises the pilot of current weather conditions, and directs the flight into the arrival queue and to the final approach course. Aircrews negotiate with both en-route and TRACON controllers for desired inflight changes, such as altitude changes to avoid turbulence, requesting to fly a direct route to save time, or requesting a desired runway for landing.

The aircraft is passed off to the tower local controller, who assures the safe separation of the arriving aircraft stream, issues the landing clearance, and instructs the pilot where to exit the runway after landing. The aircraft will then follow instructions from the ground controller, and possibly the ramp tower controller, to taxi to the arrival gate.

Operation Control

Operation control involves rescheduling equipment and rematching appropriately qualified crews with equipment in response to disturbances in the schedule, such as those caused by inclement weather. Operational control demands real-time solutions, which are typically obtained by essentially heuristic methods, although the methods usually are implemented with computers. Different carriers may have different policies regarding the restoration of normal operations. For example, one major U.S. carrier told us that they emphasize the preservation of revenue, while another told us their goal is to return to normal operations as soon as possible.

The Air Traffic Control Systems Command Center in Herndon, VA monitors all the flight traffic in U.S. It issues regional ground hold commands if the traffic congestion is at or will reach a level such that the flights to that region will experience excessive airborne delays or diversions. The triggering events for ground hold decisions are usually bad weather or the failure of ATC systems. The ground hold program is done in order to save aircraft, crew, and passengers the need to delay in the air in regions predicted to experience unusually high congestion. The Collaborated Decision Making (CDM) program is now pre-coordinated with those airlines in the affected region, which allows the airlines themselves to begin mitigation strategies prior to full implementation of the ground hold program.

Chapter 2

Current and Future Unconstrained Air Traffic Demand

This chapter identifies current air traffic demand and forecasts *unconstrained* air traffic demand in the future when the delay and congestion due to limited air traffic capacities are assumed *not* to be binding constraints on air traffic growth.

The term *air traffic demand* is only loosely defined. It can mean anything from aircraft operations to passenger enplanements on different aggregate levels, but we are primarily interested in the *schedule* of the air travel.

Specifically, a schedule is a planned service from the origin airport to the destination airport, leaving at a certain time and arriving at a certain time, operated by an air carrier using certain equipment. At present, we ignore the operator and the equipment of the schedule for reasons that will be outlined in the subsequent section entitled “Air Traffic Schedule in the Future.” NASA requested that we study the years 2005, 2010, and 2015 as the “future” for this study.

If we make time discrete by dividing a day into a certain number of periods, e.g., hour-long epochs, then a day’s schedule for 64 NAS airports will be represented by a matrix, $\{s_{ijkl}\}$, where $i, j \in I = \{0,1,\ldots,64\}$, and $k, l \in K = \{0,1,\ldots,23\}$. Here i and j are the indices of the airports in the LMINET, where 0 represents an out-of-network airport; and k and l are the time indices of the departure and arrival, respectively. The schedule, s_{ijkl}, is the number of flights from airport i to airport j that depart in the epoch k and arrive in the epoch l.

AIRPORT SELECTION IN THE STUDY

Throughout this report, we will often refer to the Federal Aviation Administration (FAA) large hub airports and the LMINET airports. The FAA classifies an airport as a large hub if it has more than 1 percent of domestic enplanements. Currently, there are 29 large hub airports,[1] which account for 68.1 percent of total

[1] The 29 FAA large hub airports are ORD, ATL, LAX, DFW, SFO, MIA, DEN, JFK, DTW, PHX, LAS, EWR, STL, MSP, BOS, IAH, MCO, SEA, HNL, CLT, LGA, PIT, SLC, PHL, CVG, DCA, SAN, BWI, and TPA.

domestic enplanements [12]. There are 64 LMINET airports,[2] which are a superset of the FAA's 57 pacing airports (a set of airports that the FAA has used to study flight operations in the NAS). The 64 LMINET airports contribute 84.9 percent of total domestic enplanements and about 85 percent of total domestic operations as reported by the Department of Transportation's (DOT's) T-100 data. The locations of the LMINET airports are depicted in Figure 2-1.

Figure 2-1. LMINET Airports

Since most of the flight delays happen at these busy airports, whether represented by the FAA's 29 or LMINET's 64 airports, restricting our study to them will filter out unhelpful noise in the results due to operations at the smaller airports and will not materially affect our conclusions.

FAA Terminal Area Forecast

The Terminal Area Forecast (TAF), published annually by the FAA, has several data tables for the total annual enplanements, operations, and various FAA workload measures for the set of airports and control towers that the FAA tracks. Each table has several columns to give more detailed information, e.g., the enplanements can be domestic or international. For the most recent TAF, released in

[2] The 64 LMINET airports are ABQ, ATL, AUS, BDL, BNA, BOS, BUR, BWI, CLE, CLT, CMH, CVG, DAL, DAY, DCA, DEN, DFW, DTW, ELP, EWR, FLL, GSO, HOU, HPN, IAD, IAH, IND, ISP, JFK, LAS, LAX, LGA, LGB, MCI, MCO, MDW, MEM, MIA, MKE, MSP, MSY, OAK, ONT, ORD, PBI, PDX, PHL, PHX, PIT, RDU, RNO, SAN, SAT, SDF, SEA, SFO, SJC, SLC, SMF, SNA, STL, SYR, TEB, and TPA.

December 1998, the data from 1976 to 1997 are the annual totals reported by the airport control towers, while the data from 1998 to 2015 are the predicted values.

The Airport Council International sponsors the annual FAA Commercial Aviation Forecast Conference every year, and 1999 is its 24th. The FAA not only updates its TAF every year but also improves the forecast's methods constantly. The TAF has become the *de facto* official aviation demand forecast. In this report, we are interested in the TAF of operations for the LMINET airports.

The FAA derives forecasted operations in the TAF in the following way [19]:

1. It forecasts the enplanements based on outputs of socioeconomic models, such as gross domestic product (GDP) and demographic growth rates, with due consideration of originating traffic and connection traffic. Each major airport has its own specific models.

2. It forecasts the load factors to and from each airport based on the demand, fare yield, and airlines cost.

3. It forecasts the average number of seats per aircraft for arrivals and departures at the airport.

4. It divides the forecasted enplanement by the forecasted load factor and by the forecasted average number of seats per aircraft to get forecasted operations.

In deriving the forecasts, flight delays due to traffic congestion are never explicitly considered. Implicitly, the TAF assumes that airport and ATC capacities will grow to meet the potential demand.

Table C-1 in Appendix C shows the FAA's values for total operations and their respective growth rates from the 1997 level at the LMINET airports for 1997, 2005, 2010, and 2015. Since our model will treat commercial operations represented by OAG and the GA operations differently, the traffic and growth rates are listed separately. We used the total of *air carrier, air taxi,* and *itinerant GA* in the TAF as the airport operations measure. Air carrier and air taxi are the operations of scheduled air transport service corresponding to the OAG; air taxi data are for aircraft with less than 60 seats, which are typical of commuter operations.

One can see that all the airports will enjoy positive total and commercial operations growth during the period, but there are many airports with negative GA operations growth. This may imply that the commercial traffic growth will be at the expense of GA operations. For all airports reported in FAA's TAF but not included in the 64 LMINET airports, they are aggregated at the last rows of the table under the airport designated as "OTR."

Tables 2-1 and 2-2 compare LMINET to the network for operations and enplanements, respectively.

Table 2-1. LMINET Airports Versus the Total Operations (Millions)

	Count	Operations			Growth rate (%)	
		1997	2005	2015	1997–2005	2005–2015
Large hubs	29	13.8	16.2	20.3	2.07	2.27
Medium hubs	42	9.3	11.0	13.1	2.10	1.75
Small hubs	68	8.4	9.4	10.4	1.37	1.02
Non-hub towers	312	32.3	35.5	38.9	1.19	0.92
Total	451	63.9	72.1	82.6	1.53	1.37
LMINET airports	64	20.9	24.6	30.3	2.06	2.11

Table 2-2. LMINET Airports Versus the Total Enplanements (Millions)

	Count	Enplanements			Growth rate (%)	
		1997	2005	2015	1997–2005	2005–2015
Large hubs[a]	29	430.2	577.1	806.8	3.74	3.41
Medium hubs[b,c]	42	139.2	193.7	270.1	4.21	3.38
Small hubs[d]	68	43.5	57.3	73.4	3.52	2.50
Non hub towers	310	16.6	20.7	26.0	2.80	2.28
Total	449	629.5	848.9	1,176.4	3.81	3.32
LMI airports	64	534.3	722.3	1,008.2	3.84	3.39
Share (%)	—	84.9	85.1	85.7	—	—

Source: Department of Transportation, *Aerospace Forecasts*, *Fiscal Years 1999–-2010*, Report No. FAA-APO-99-1, Federal Aviation Administration, Office of Aviation Policy and Plans, Statistics and Forecast Branch, Washington, DC, March 1999.

[a] > 1.0 percent of total enplanement.

[b] > 0.25 percent of total enplanement.

[c] The 42 medium hub airports are ABQ, ANC, AUS, BDL, BNA, BUF, BUR, CLE, CMH, COS, DAL, ELP, FLL, GEG, HOU, IAD, IND, JAX, MCI, MDW, MEM, MKE, MSY, OAK, OGG, OKC, OMA, ONT, PBI, PDX, RDU, RNO, RSW, SAT, SDF, SJC, SJU, SMF, SNA, TUL, TUS, and GUM.

[d] > 0.05 percent of total enplanement.

Figures 2-2 and 2-3 graphically depict the LMINET airport annual operations and enplanements for 1997 through 2015.

Figure 2-2. Total LMINET Airport Annual Operations (Millions)

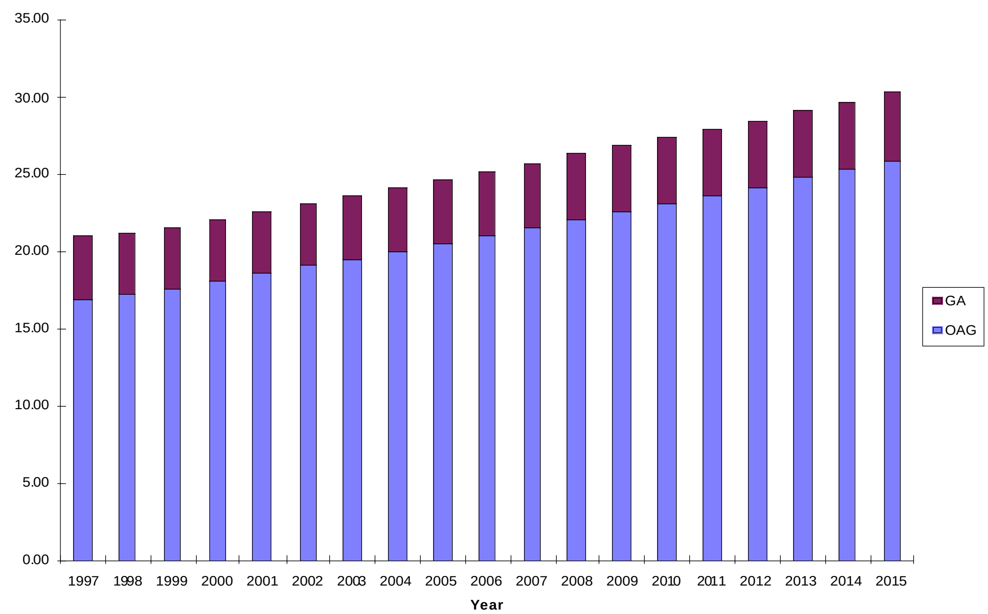
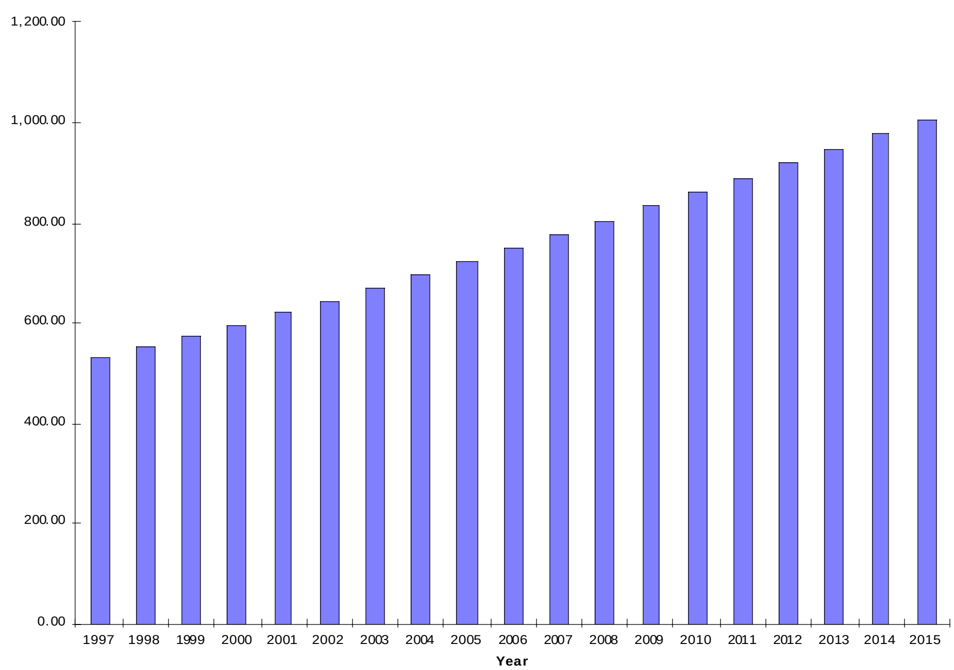


Figure 2-3. Total LMINET Airport Annual Enplanements (Millions)



CURRENT AIR TRAFFIC SCHEDULE

Date Selection

Since the latest real data about airport operations in the FAA's TAF is from 1997 (which we will use to project the future air traffic service schedule), the schedules in 1997 must be the ones considered to be current. However, typically, a carrier has a few major schedule changes each year and minor schedule changes can happen on a day-to-day basis. We need to select a date, or a few dates, that will represent a typical airline and GA operations.

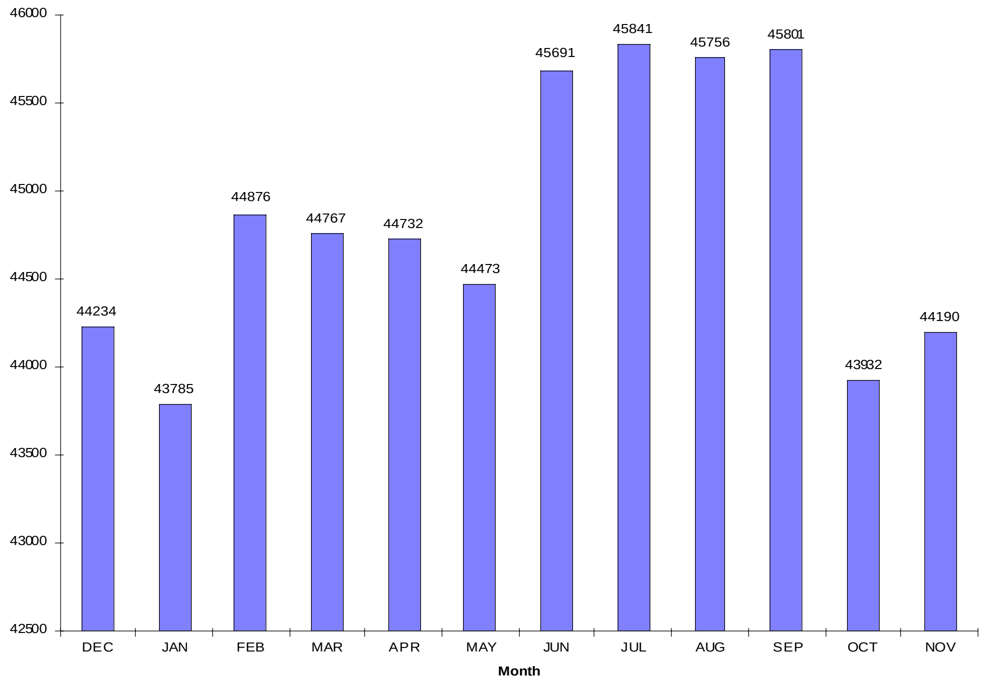
Since GA is about only 15 percent of the total operations in the LMINET airports, and they are not scheduled service, our selection will be based on the scheduled commercial air traffic service represented by the OAG. Using available data, we used the period of December 1, 1996, to November 30, 1997, as the year of 1997. Since the operation growth rate is about 2 percent each year, this approximation may cause about a 0.2 percent underestimation of total OAG operations in 1997. However, this potential underestimation has no impact on the analysis within a one-year cycle.

Figure 2-4 demonstrates how the traffic demand can be categorized from lowest to highest into the following three groups:

1. October to January
2. February to May
3. June to September.

Note that the y-axis origin of Figure 2-4 is not zero, and that the demand variation is actually small: the difference from February, the lowest month, to July, the highest month, is less than 5 percent.

Figure 2–4. Average Total Daily Operations in LMINET Airports by Month

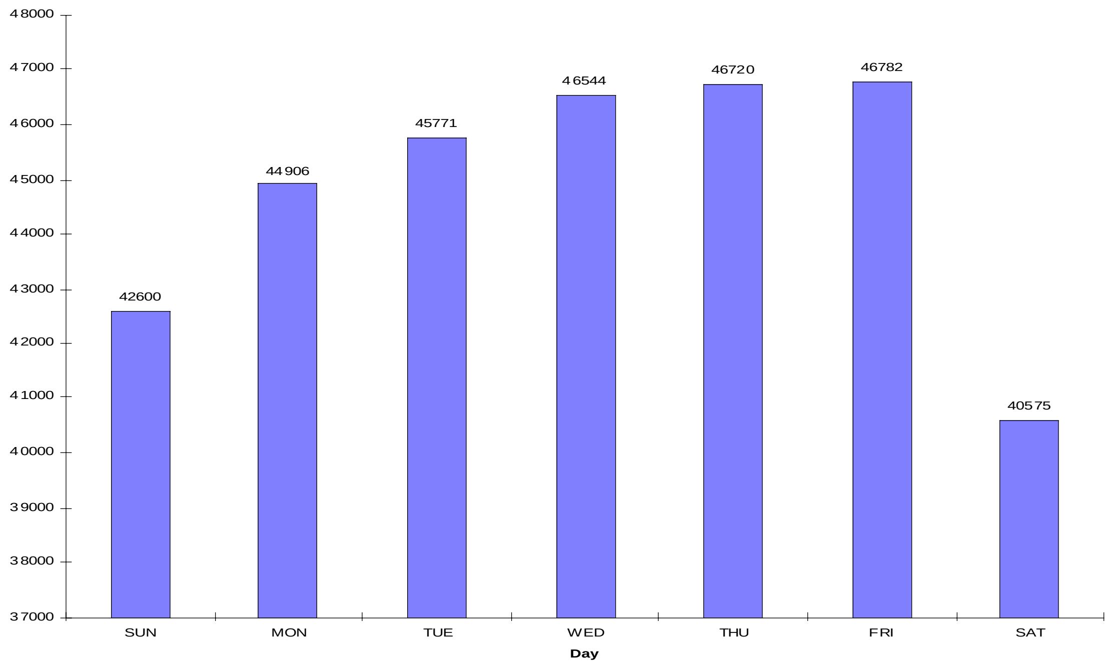


Data source: OAG

Figure 2-5 shows how operations, on the average, follow a strong weekly pattern. The average pattern is not followed during Christmas and New Year's and a brief period at the end of October. Since there is no major holiday at the end of October, we suspect that the disruption of the weekly demand pattern and the low demand is due to the data quality, which also results in the low demand figure for October.

National holidays have virtually no impact on the total operations except during Christmas and New Year's. The traffic service reaches its highest level from the mid-June through mid-September, which not only contains the highest weekday service, but also, more pronouncedly, the highest weekend service.

Figure 2–5. Average Total Operations in LMINET Airports By Day Of Week



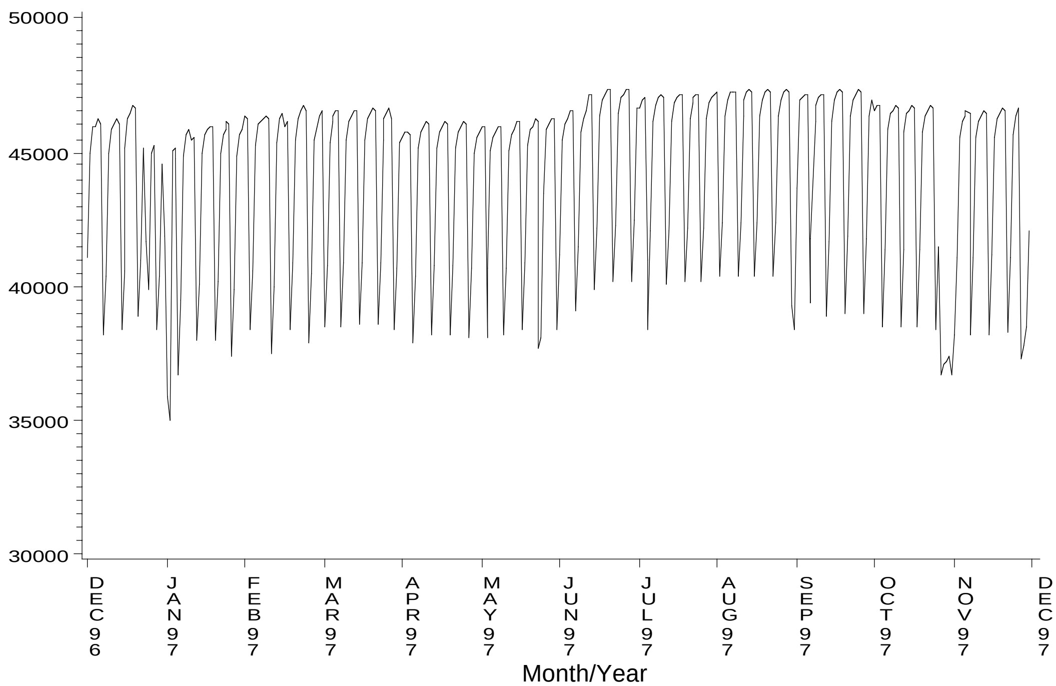
Data source: OAG

The amount of service is lowest on Saturday, and the amount of service increases daily from Monday during one-week cycle until it culminates on Friday. The difference in the amount of service between Friday and Saturday is more than 15 percent of the daily total.

June 19 is the date with the most operations (47,325) while January 2 is the date with least operations (34,973) in 1997 within the 64 LMINET airports. We recommend using June 19, 1997, as the date to extract schedules in our study. Any traffic generated for the future must be interpreted as the date during the year with most traffic, which happens to be in the summer.

Figure 2-6 illustrates that there is not much variability of total operations among the days within the same day-of-week category. From Table 2-3, one can see that the day with the maximum number of operations is just 1.7 percent more than the day whose Cumulative Distribution Function (CDF) is 75 percent. This further justifies the use of the day with maximum operations, since it is not an extreme outlier.[3]

Figure 2-6. Total Daily Operations in LMINET Airports from December 1, 1996 to November 30, 1997



Data source: OAG

Table 2-3. Cumulative Distribution Function of Total Daily Operations in LMINET Airports

Operations	46,542	47,108	47,217	47,325
Cumulative distribution function	75%	90%	95%	100%

[3] The airline cost and fare increase due to flight delays are based on the more aggregate figures, not on the ones incurred in a day. However, since the total delays can be approximated as a log-linear function of the total demand and what matters in ACIM is the annual percentage increase of delay, or the slope in the log-linear demand-delay model, the selection of days to run traffic does not have a major impact on the results as long as we use consistent days across the time periods.

Traffic Adjustment

We based demand for scheduled air transport service on the schedule published by the OAG. We constructed the time variation of GA demands from data recorded in the FAA's Enhanced Traffic Management System (ETMS).

Since the OAG schedule is the planned rather than observed air traffic schedule, and only the GA flights filing instrument flight rules (IFR) flight plans will be recorded in ETMS, there will be differences between the traffic reported by the OAG and ETMS and the FAA's TAF. Since the TAF is recorded by traffic control towers, which are believed reliable, both the OAG and GA schedules have to be scaled to conform to the data in the TAF.

Table 2-4 lists the traffic adjustment factors for each LMINET airport. We first compute the total planned annual commercial operations, per airport, based on the entire 1997 OAG. The Commercial Adjustment Factor, α, is given by the commercial operations in the TAF (air carrier and air taxi) divided by the operations given by the OAG. The Total Adjustment Factor, γ, is given by the total airport operations in the TAF (air carrier, air taxi, and itinerant GA) divided by the operations given by the OAG.

Table 2-4. Commercial and Total Traffic Adjustment Factors

Airport	α	γ	Airport	α	γ
BOS	1.02	1.09	MKE	1.15	1.47
BDL	1.16	1.59	ORD	0.98	1.02
HPN	1.04	3.47	MDW	1.25	1.90
ISP	1.00	3.54	STL	0.99	1.05
TEB	1.00	1.00	IAH	0.96	1.03
LGA	1.00	1.05	HOU	1.05	1.93
JFK	1.03	1.07	AUS	1.06	2.18
EWR	1.01	1.05	SAT	1.28	2.49
PHL	1.06	1.19	DAL	1.26	2.24
BWI	1.09	1.19	DFW	1.02	1.13
DCA	1.03	1.22	MSP	1.00	1.13
IAD	1.03	1.26	MCI	1.01	1.08
GSO	1.23	2.21	DEN	0.97	1.02
RDU	1.11	1.64	ABQ	1.04	1.57
CLT	1.05	1.20	ELP	1.13	1.89
ATL	1.02	1.05	PHX	1.05	1.24
MCO	1.04	1.14	SLC	1.10	1.38
PBI	1.07	2.29	LAS	1.17	1.48
FLL	1.10	1.62	SAN	0.95	1.02

MIA	1.06	1.21	SNA	0.98	3.60
TPA	1.10	1.30	LGB	2.15	39.53
MSY	1.08	1.27	LAX	0.97	1.00
MEM	1.35	1.62	BUR	1.41	2.55
BNA	1.09	1.60	ONT	1.18	1.44
SDF	1.22	1.51	RNO	1.13	1.64

Table 2-4. Commercial and Total Traffic Adjustment Factors (Continued)

Airport	α	γ	Airport	α	γ
CVG	1.00	1.03	SMF	1.09	1.32
DAY	1.12	1.61	OAK	1.71	2.94
CMH	1.33	1.67	SFO	0.97	1.03
IND	1.46	1.88	SJC	1.01	1.69
CLE	1.05	1.17	PDX	1.10	1.27
DTW	1.04	1.23	SEA	1.02	1.03
PIT	1.03	1.09	OTR	1.05	1.29
SYR	1.21	1.71			

It is obvious from the factors' definitions that if we scale the OAG operation by the adjustment factors α and γ, we will get the *actual* commercial operations and total operations, respectively. Since commercial and GA operate on different schedules and adjust at different rates, a GA adjustment factor, β, is needed.

Let T_{Total}, $T_{Commercial}$, T_{OAG}, T_{GA}, T_{ETMS} be the traffic indicated by the subscripts. By the definitions,

$$\mathrm{T}_{Total} = \mathrm{T}_{Commercial} + \mathrm{T}_{GA}, \qquad \text{[Eq. 2-1]}$$

$$T_{Total} = \gamma T_{OAG}, \qquad \text{[Eq. 2-2]}$$

$$T_{Commercial} = \alpha T_{OAG}, \text{ and} \qquad \text{[Eq. 2-3]}$$

$$T_{GA} = \beta T_{ETMS}, \qquad \text{[Eq. 2-4]}$$

we have

$$\beta = (\gamma - \alpha) \times T_{OAG}/T_{ETMS}. \qquad \text{[Eq. 2-5]}$$

Since we do not have any particular knowledge about the missing flights from OAG to commercial, and from ETMS to GA, we have to assume that they are random or that the missed flights are proportional to the ones in the current schedule. The scaling-up of OAG for commercial traffic takes an application of the Fratar algorithm, and the scaling-up from ETMS for GA traffic takes the simple form of multiplying all the flights by the adjustment factor, β, of the departure airport, based on the same arguments that will be presented in the next section.

AIR TRAFFIC SCHEDULE IN THE FUTURE

The future air traffic demand, expressed in terms of the schedule, s_{ijkl}, must be constructed, although the only thing we know is the total airport operations. In fact, generating demand schedules for the entire network is a challenging task. Although the academic literature is rife with models and algorithms, they are geared to providing the forecast of single variable systems or a non-networked multivariable system.

Two major intellectual challenges exist:

- the interaction of the NAS network's nodes and arcs and the possibility of achieving the goal of a specific traffic level via different means and
- the prediction of air carriers' behavior, even at some high aggregate level.

This section presents our modeling considerations and the algorithm that we used to forecast future air traffic schedules.

Modeling Assumptions

Our modeling is based on available data and models; on their integration; and, more importantly, on the desired properties of our forecast. We require our approach for forecasting the unconstrained air traffic demand to satisfy the following:

1. The schedule provided by the air carriers is the variable of interest, which reveals everything about air carriers' operations.
2. We will construct an industry-wide model instead of one that integrates carrier-specific models. The air transport industry in the United States is an oligopoly, consisting of 10 major carriers with about 90 percent of total domestic operation and three dozen or so affiliated and unaffiliated commuter, cargo, and chartered passenger and cargo carriers. If we just concentrate on having individual models for each of the 10 major passenger carriers—if we could accomplish the tremendous amount of work involved—it is still impossible to predict the industry configuration or market share in the future in this dynamic environment. The recently announced virtual merger between Northwest Airlines and Continental Air-

lines, and the marketing alliance between the two former foes, American Airlines and US Airways, are good examples of these difficulties.

Taking the whole industry together, while still assuming the existence of competition among the carriers, we avoid attempting to predict winners and losers in the competition. A representative of one major U.S. carrier told us that his airline aggressively seeks opportunities to grow, since if it

does not, someone else will. This means that the air carriers put their resources where the demand is on the aggregate level. On the other hand, we do not really need an air carrier-specific model if our model will be used by other models to quantify the benefits of new air traffic management (ATM) procedures or decision support tools. Individual air carriers will indirectly benefit from our industry-wide model, in that it is up to them to compete for market share in a way that best utilizes their resources.

3. The FAA's TAF will be used as an initial input, so the future schedule we derive must meet the TAF at the airport level. Because of the way the TAF is produced, delineated previously in this chapter, we assume that airport and ATC service capabilities will grow accordingly, not to constrain the traffic demand.

4. The traffic growth rate between two cities must be proportional to the traffic growth rates in both cities, respectively.

5. Air carriers' operation practices will be unchanged. Specifically, we assume that the current air carriers' operations are rational and will continue to be in the future. By "rational," we mean that the air carriers, being commercial companies, will try to maximize their profits by putting their resources or schedules where the demand is. Battling for market share, just for the sake of market share by providing more schedules than demand, is not rational behavior. This is believed to be a good assumption, since the air transport industry appears to have finally reached maturity after 2 decades of deregulation. Evidence of this is provided by comparing the record profits and relative stability enjoyed by the industry in the past few years to the record losses, massive traffic growth, labor disputes, and industry instability (with a plethora of low-cost start-up carriers and merger and acquisition activities) seen right after the deregulation in 1980s and early 1990s.

   The assumption of rationality of air carriers can be decomposed into the following:

   a. The current OAG schedule is the best schedule to meet air travel demand. One example is Continental Airlines' decision in the past few years to cancel its hubs at Denver, and Greensboro/High Point and redeploy the flights to Houston and Newark to get better yields.

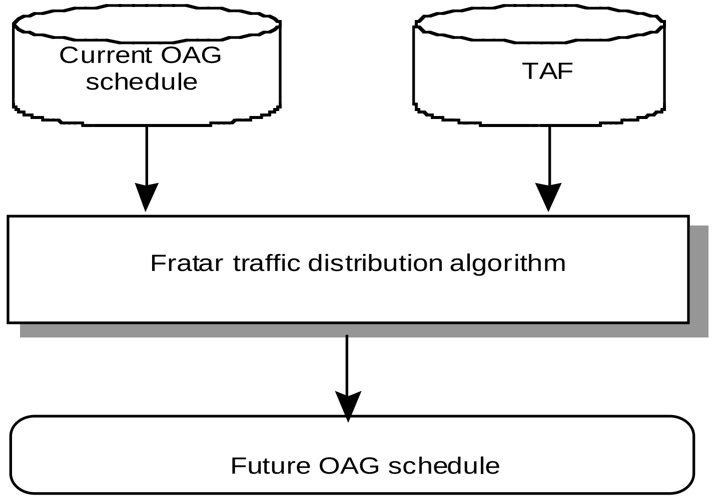
b. The air carriers will continue to conduct bank operations in hub airports. Since airline deregulation in 1978, the carriers have had the freedom to design their schedules as they see fit except for a few slot-controlled airports. Since then, air carriers have consolidated their operations to concentrate on a few hub airports, which are characterized by alternating banks of arrivals and departures. There are two major advantages of bank operations: first, the number of markets, through connection at the hub, is massively expanded—offering travelers choices that cannot be made through point-to-point operations; second, the airline that has the dominant market share at the hub cities commands premium fares.

6. The time-of-day demand pattern will not change. Given the total number of people willing to travel from A to B in a day, research by airlines and Boeing shows that the distribution of that demand across the day depends on the local departure and arrival times and the journey time, where business travelers and leisure travelers may have different demand patterns, and, of course, different demand elasticities. Thus, unless there are new technologies that will drastically reduce the journey time, the travelers' time-of-day demand patterns will not change.

Fratar Algorithm

The Fratar algorithm is the most widely used method for generating trip distributions based on the terminal area forecast. Both the DOT and FAA have used it in their transportation planning models, such as NASPAC, an event simulation model of NAS. A schematic diagram of the algorithm is shown in Figure 2-7.

Figure 2-7. The Fratar Traffic Growth Distribution Algorithm



The daily traffic, t_{ij}, from airport i to airport j, total daily departures, d_i, from airport i, and total daily arrivals, a_j, to airport j are related to the schedule, s_{ijkl}, as follows:

$$t_{ij} = \sum_{kl} s_{ijkl}, \qquad \text{[E}$$

$$d_i = \sum_j t_{ij}, \qquad \text{[Eq. 2-7]}$$

$$a_j = \sum_i t_{ij}. \qquad \text{[Eq. 2-8]}$$

If the schedule is balanced, or the network does not have any sinks, then $d_i = a_i$, $\forall\ i \in I$.

Let D_i, $i \in I$ represent the total number of departures in the target year taken from the forecast. The Fratar method is an iterative algorithm that takes the following steps:

Step 0:

Assign t_{ij}, d_i, a_j, $\forall i, j \in I$, based on the current year schedule.

Step 1:

$$g_i = \frac{D_i}{d_i}, \forall i \in I, \qquad \text{[Eq. 2-9]}$$

Step 2:

$$T_{ij} = t_{ij} \times g_i \times g_j \times \frac{1}{2}\left(\frac{d_i}{\sum_m t_{im} \cdot g_m} + \frac{a_j}{\sum_m t_{mj} \cdot g_m}\right), \forall i, j \in I \quad . \qquad \text{[Eq. 2-10]}$$

Step 3:

If $\sum_m T_{im} = D_i, \forall i \in I$, then go to step 4

else

$t_{ij} = T_{ij}$, $\forall i, j \in I$, and update d_i, a_j, $\forall i, j \in I$ accordingly; go to step 1

Step 4:

Compute the traffic growth factor, r_{ij}, $\forall i, j \in I$, by dividing the traffic, T_{ij}, in the target year by the one in the current year; compute the schedule, S_{ijkl}, in the target year by multiplying the schedule in the current year by the traffic growth factor, r_{ij}. Stop.

Now let us check that the schedule in the target year made by the Fratar algorithm has the desired properties. First, the schedule always will meet the terminal departure totals predicted in the TAF, which is embedded in the algorithm.

Second, $r_{ij} = r_{ji}$, which means the traffic growth is nondirectional. This is an implicit desired property in a travel network, although not explicitly stated in the previous subsection.

Third, the growth factor is uniform across the entire day, which is a desired property if we assume that the current schedule is rational and the travelers' time-of-day demand pattern will not change.

The fact that the growth factor is uniform across the day implies another property of the schedule in the target year: the airport traffic is dynamically balanced and the bank operations in hub airports are preserved. Let d_{ik}, a_{ik}, $\forall i \in I$, $\forall k \in K$, be the total departures and arrivals in time k at airport i.

$$d_{ik} = \textstyle\sum_{jl} s_{ijkl.}$$

$$a_{ik} = \textstyle\sum_{jl} s_{jilk}.$$

An airport i is said to be dynamically balanced if $d_{ik} = a_{ik}$, $\forall k \in K$, which means there are no idle aircraft sitting on the ground. In reality, a flight has to spend some time in the terminal before taking off, but we will keep this simple definition, and real operations can be modeled by shifting the time index. Let D_{ik}, A_{ik}, $\forall i \in I$, $\forall k$

$\in K$ be the total departures and arrivals at airport i at time k in the target year. By the Fratar algorithm,

$$D_{ik} = \sum_{jl} s_{jkl} = \sum_{jl} r_{ij}\, s_{ijkl} = G_i \sum_{jl} u_j\, s_{ijkl}, \qquad \text{[Eq. 2-11]}$$

$$A_{ik} = \sum_{jl} S_{jilk} = \sum_{jl} r_{ji}\, s_{jilk} = \sum_{jl} r_{ij}\, s_{jilk} = G_i \sum_{jl} u_j\, s_{jilk}, \qquad \text{[Eq. 2-12]}$$

where

$$G_i\, u_j = r_{ij},\ \forall i, j \in I, \textit{ and } \sum_{jl} u_j = 1. \qquad \text{[Eq. 2-13]}$$

The right-hand sides of D_{ik} and A_{ik} resemble the expectations of the product of two discrete random variables. If two random variables are independent, then the expectation of their product is equal to the product of their expectations. If we assume that the traffic growth rate is independent of the current schedule, which is a reasonable assumption, then

$$D_{ik} \cong G_i\, (\textstyle\sum_{jl} u_j)(\sum_{jl} s_{ijkl}) = G_i d_{ik.}$$

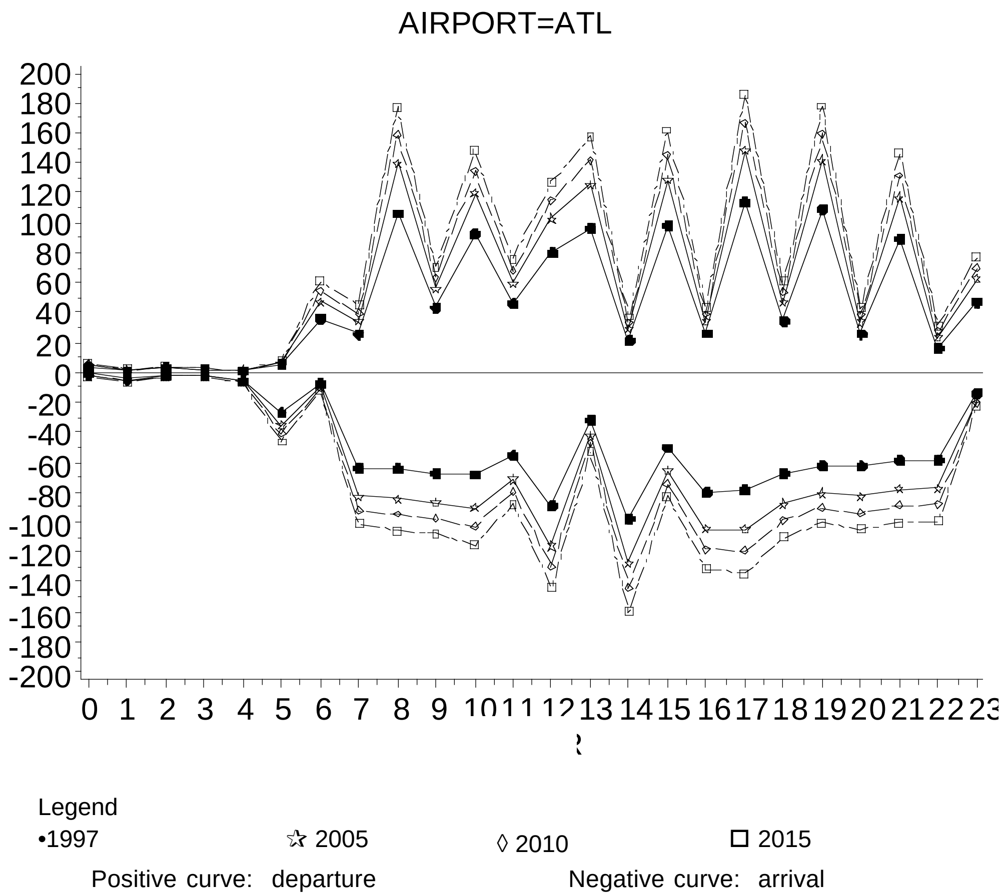
Similarly,

$$A_{ik} \cong G_i a_{ik}.$$

Since $d_{ik} = a_{ik}$, $\forall i \in I$, $\forall k \in K$, then $D_{ik} \cong A_{ik}$. And, interestingly, G_i must be the growth factor implied by the TAF in order to satisfy the binding terminal total departure constraint.

Figure 2-8 shows an example of applying our method to ATL.

Figure 2–8. Current and Forecast Unconstrained Operations at ATL



Chapter 3
Methodology and Strategy Scenarios

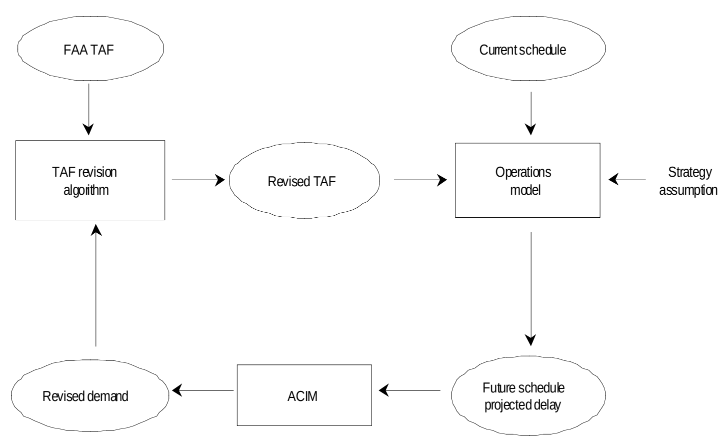
GENERAL METHODOLOGY

To evaluate the merits of various operating concepts in meeting the projected future growth in demand, it is necessary to develop a comprehensive, yet flexible, methodology. This section describes the technical approach we followed to satisfy this requirement.

Model Schematic

Our present methodology is adapted from our previous work related to assessing the economic impact of air traffic congestion [22]. The basic approach is to link delay forecasts from the Operations Model[1], which are driven by traffic projections at the airports, with industry-level supply and demand characteristics imbedded in the Air Carrier Investment Model (ACIM). The impact of various operating strategies to alleviate congestion and its resultant airline delays can be analyzed by modifying parameters of the Operations Model. The result is a revised forecast that can be compared with the unconstrained forecast (FAA TAF) to measure the success of the proposed strategy in accommodating air travel demand. Figure 3-1 illustrates this approach.

Figure 3-1. General Methodology



[1] The Operations Model includes the airport delay elements of the LMINET model plus additional analysis software.

As shown in Figure 3-1, the general methodology begins with the Operations Model, which takes projected airport operations growth rates, combined with the current traffic schedule and the operational strategy assumptions, to generate the future traffic schedule and delay estimates. Forecasted future demand is in the form of the total number of flights for a given airport-pair in an hour based on the Fratar algorithm detailed in Chapter 2. The delay computation is detailed in Appendix B, which is the pure delay against the optimal, not against the schedule which may have padding. Because the Operations Model computes airport delays based upon traffic demand forecast according to the traffic schedule, delays are amplified by a set of multipliers to account for the rippling delays of delayed aircraft for the rest of the day. The delay multipliers are derived by American Airlines using real data [21]. In general, the earlier in the day the delay occurs and the longer the delay lasts, the larger the delay multiplier is.

Next, total delays computed from the Operations Model are used to generate block time changes. Increases in block times, all else being equal, increase airline costs, which will generate a revised (reduced) industry forecast.

The revised RPM forecast from the ACIM is the variable in which we are most interested. The system starts with the unconstrained operations growth rates from FAA's TAF. Our idea is to modify the airport operations growth rates based on the revised RPM forecasts from the ACIM, which is accomplished through the TAF revision algorithm that will be detailed later. The system converges when total system traffic (operations or RPMs) from both the Operations Model and the ACIM agree.

Only good weather conditions are considered in the analysis, since we are interested in the long-term strategic response of the flight schedule to congestion. Because air carriers develop their schedule under the assumption of good weather conditions, it is not appropriate to consider the impact of adverse weather conditions in our delay calculations.

Some airports can accommodate the projected demand without generating much additional delay. However, many of the airports are severely constrained by a lack of capacity and generate projections for large increases in delay in future [14, 15, 16, 17]. Therefore, additional methods are required to ration the limited capacity so that demand ultimately matches supply.

One approach to reduce demand to match capacity is to simply eliminate operations at congested airports. Although the Operations Model can implement this approach, the selection of which flights to eliminate is quite arbitrary. Therefore, we developed an alternative approach that uses the ACIM to ration the limited capacity through higher fares.[2] The premise of using the ACIM to evaluate the impact of delay on air travel demand is that increases in air carrier operating costs (due to congestion) are passed along to consumers in the form of higher fare yields, which further slow the growth rate of demand. Thus, an equilibrium is achieved in which the costs of delay are balanced by the passengers' willingness to pay for additional travel. Under this approach, the ACIM produces an estimate of the reduction in aggregate air travel demand due to the increased costs of congestion.

ACIM Calibration

In order to use the ACIM for this study, we first updated the airline cost and operational data to 1996. We also had to calibrate the model to the latest *FAA Aerospace Forecasts* [19]. In Table 2 of their forecasts, the FAA predicts that U.S. gross domestic product (in constant dollars) will grow at a compound annual rate of 2.528 percent during the period 1996 to 2010. In Table 6, the FAA predicts that fuel prices will decline by 0.774 percent per year and that system-wide average seats per aircraft will increase by 0.496 percent per year over the same timeframe. In Table 14, the FAA predicts that load factors will increase by 0.576 percent per year during the period 1996 to 2000 and remain basically constant from 2000 to 2010. Finally, in Table 20, the FAA predicts that average seats per aircraft for U.S. regional and commuter airlines will increase by 2.346 percent per year during the period 1996 to 2010. We incorporated all of these FAA predictions and set adjusted operating profit margins to 8.0 percent to calibrate the two forecasts. A comparison is shown in Table 3-1.

Table 3-1. Comparison of Forecasts

Year	FAA (billions of RPMs)	FCM (billions of RPMs)
2000	671.5	671.5
2005	843.9	843.6
2010	1060.2	1060.6
2015	1332.0*	1331.4

* = the growth rate from 2005 to 2010 was extrapolated to the following 5-year period.

Traffic-Reduction Distribution Algorithm Based on Delay

While the Operations Model needs and outputs detailed data, including airport-specific traffic growth rates, schedules, and delays, the ACIM requires and outputs aggregate data including the productivity change due to delay and the total

[2] See Reference [20] for more information on the ACIM. The ACIM consists of four core modules: the U.S. Econometric Module, U.S. Functional Cost Module (FCM), Asian Econometric Module, and European Econometric Module. The U.S. Econometric Module uses an econometric approach to estimate air carrier costs, while the FCM uses activity-based costing. For this study, we employed the FCM exclusively.

system RPM traffic. Without modification, total system traffic will differ between the two models. The revised traffic growth rates are the ones that will make the two traffic figures from the Operations Model and the ACIM agree. This section presents an algorithm that will modify the airport-specific traffic growth rates based upon flight delays.

A uniform reduction of operations across all LMINET airports is certainly undesirable since the delays are unevenly distributed among the airports. It seems that the airports with higher average delay per flight ought to reduce more operations. However, this is a complicated matter because there is a nonlinear relationship between airport operations and delays.

We employ an iterative algorithm in which we continuously modify the traffic growth rates for each airport from the baseline year 1997 to the target years. We will skip the subscript for the target year identification since the algorithm treats all target years in the same way, and there is no direct relationship among the target years in the algorithm that follows.

The symbols of definition of the variables used for an airport, $i \in \{1,2,\ldots,64\}$, in our 64 LMINET airport set are as follows:

$n_i^{(k)}$ is the total number of commercial operations from the Operations Model in the target year at the *k-th* iteration.

$d_i^{(k)}$ is the average delay per operation in the target year at the *k-th* iteration[3].

$t_i^{(k)}$ is the revised commercial traffic growth rate to the target year at the *k-th* iteration.

$n_i^{(0)}$ is the total number of commercial operations in the baseline year of 1997.

$d_i^{(0)}$: the average delay per operation in the baseline year of 1997;

$t_i^{(0)}$: the unconstrained commercial operations growth rate to the target year.

Conceptually, if we follow the log-log linear model widely used in economics literature, we have for any airport $i \in \{1,2,\ldots,64\}$

$$\%\Delta n_i^{(k+1)} = t_i^{(0)} - \varepsilon_i^{(k)} ?\%\Delta d_i^{(k)}, k = 1,2... \qquad \text{[Eq. 3-1]}$$

where

[3] Because the runway and taxiway delays in the airports account for the overwhelming majority of the total delay of a flight, the average of flight delay is approximated as the delays in the airport in this study [14,15]. The network effect of a flight delay at an airport is accounted for by multiplying it by a factor derived by using real data in the American Airlines network [21]. The factors are in a range of 1 to a number as large as 7, depending on the time of the delay and the amount of delay. In general, the factor is close to 1 if the delay is small or it occurs late at night, and it is high if the delay is large and it happens in the early morning.

$$\%\Delta n_i^{(k)} = \frac{\Delta n_i^{(k)}}{n_i^{(0)}} = \frac{n_i^{(k)} - n_i^{(0)}}{n_i^{(0)}}, k = 1,2,... \qquad \text{[Eq. 3-2]}$$

and

$$\%\Delta d_i^{(k)} = \frac{\Delta d_i^{(k)}}{d_i^{(0)}} = \frac{d_i^{(k)} - d_i^{(0)}}{d_i^{(0)}}, k = 1,2,... \qquad \text{[Eq. 3-3]}$$

Equation 3-1 states that the traffic operation percentage growth is determined by a slew of factors that are summarized by the unconstrained growth rate $t_i^{(0)}$ and is negatively proportional to the percentage increase of delays per operation at that airport. Clearly, $\varepsilon_i^{(k)}$ is the elasticity of delay to traffic. Our idea to find the solution in which the total traffic estimates from both models converge is by forcing $n_i^{(k+1)}$ to be $n_{i,ACIM}^{(k)}$, i.e., letting the operations in the Operations Model during the next iteration equal the ones prescribed by the ACIM.

From Equations 3-1 and 3-2,

$$\Delta n_i^{(k+1)} = (t_i^{(0)} - \varepsilon_i^{(k)} \ ?\%\Delta d_i^{(k)})\ ?n_i^{(0)}, k = 1,2,... \qquad \text{[Eq. 3-4]}$$

Thus, the overall change of operations in the network from the current year to the target year is given by

$$\Delta N^{(k+1)} = \sum_i \Delta n_i^{(k+1)} = \sum_i (t_i^{(0)} - \varepsilon_i^{(k)} \ ?\%\Delta d_i^{(k)})\ ?n_i^{(0)}$$

$$= \sum_i t_i^{(0)} \ ?n_i^{(0)} - \sum_i \varepsilon_i^{(k)} \ ?n_i^{(0)} \ ?\%\Delta d_i^{(k)}$$

$$= \Delta N^{(0)} - \sum_i \varepsilon_i^{(k)} \ ?n_i^{(0)} \ ?\%\Delta d_i^{(k)}, k = 1,2,... \qquad \text{[Eq. 3-5]}$$

where $\Delta N^{(0)}$ is the unconstrained operation growth from the current year to the target year. If we assume[4]

$$\varepsilon_i^{(k)} = \varepsilon^{(k)} \ ?f(d_i^{(0)}, d_i^{(k)}), k = 1,2,.... \qquad \text{[Eq. 3-6]}$$

substituting Equation 3-6 with 3-5, we get

[4] This is a major assumption required by the fact that the ACIM model has only one value for elasticity. We assume here that all airports have the same proportional response to delay. This is not too farfetched considering that the same airline and ATC procedures apply to all the airports.

$$\varepsilon^{(\mathrm{k})} = \frac{\Delta N^{(0)} - \Delta N^{(\mathrm{k}+1)}_{\mathrm{Ops}}}{{}_{i}\, n_i^{(0)} \;?\; f(d_i^{(0)}, d_i^{(k)}) \;?\% \Delta d_i^{(k)}}$$

$$= \frac{\mathrm{N}^{(0)} - N^{(\mathrm{k})}_{ACIM}}{{}_{i}\, n_i^{(0)} \;?\; f(d_i^{(0)}, d_i^{(k)}) \;?\% \Delta d_i^{(k)}}, k = 1,2,... \qquad \text{[Eq. 3-7]}$$

where N_{Ops} and N_{ACIM} are the total numbers of operations indicated by the Operations and ACIM models in the target year, respectively. Since the ACIM forecasts RPMs directly, we have to covert them to operations through Table 3-2's conversion factors.

Table 3-2. System RPM to LMINET Airport Operations Conversion Factors (RPMs per Operation)

Year	1997	2005	2010	2015
Conversion factor κ	34,636	41,097	45,672	51,286

The conversion factors are derived by dividing the total unconstrained RPMs in the system by the total unconstrained operations in the 64 LMINET airports.[5] Therefore,

$$\varepsilon^{(k)} = \frac{RPM^{(0)} - RPM^{(k)}_{ACIM}}{\kappa \;{}_{\mathrm{i}}\, n_{\mathrm{i}}^{(0)} \;?\; f(d_{\mathrm{i}}^{(0)}, d_{\mathrm{i}}^{(\mathrm{k})}) \;?\% \Delta d_i^{(k)}}, k = 1,2... \qquad \text{[Eq. 3-8]}$$

Once $\varepsilon^{(k)}$ is known, it seems that we can update the commercial air traffic operation growth rate $t_i^{(k)}$ from Equation 3-4 by

$$t_i^{(k)} = t_i^{(0)} - \varepsilon_i^{(k)} \;?\% \Delta d_i^{(k)}, k = 1,2... \qquad \text{[Eq. 3-9]}$$

Indeed, we can carry out this iterative operation to find the final revised operation growth rate for each airport. However, we found, under some parameter settings, that the system may become stable even before true convergence happens, although they are quite close within a few percentage error. This is not a surprise to us since this is a numerical solution. In fact, this convinced us of the validity of our log-log linear model. The way to remedy this is through the error of the total operations between the two models during each iteration, which Equation 3-8 lacks. By Equations 3-7 and 3-9, we have

[5] Our conversion factors may be different from ones found in other data sources because the RPMs reported by the ACIM are the total system RPMs tracked by FAA whereas the operations are the ones for the 64 LMINET airports.

$$t_i^{(k)} = t_i^{(k-1)} - \alpha_i^{(k)} \, ?\%\Delta d_i^{(k)}, k = 1,2,... \qquad \text{[Eq. 3-10]}$$

where

$$\alpha_i^{(k)} = \varepsilon_i^{(k)} \, ?\%\Delta d_i^{(k)} - \varepsilon_i^{(k-1)} \, ?\%\Delta d_i^{(k-1)}$$

$$\cong \frac{N_{ACIM}^{(k-1)} - N_{ACIM}^{(k)}}{\underset{i}{} \; n_i^{(0)} \, ? f(d_i^{(0)}, d_i^{(k)}) \, ?\%\Delta d_i^{(k)}}$$

$$= \frac{N_{Ops}^{(k)} - RPM_{ACIM}^{(k)} / \kappa}{\underset{i}{} \; n_i^{(0)} \, ? f(d_i^{(0)}, d_i^{(k)}) \, ?\%\Delta d_i^{(k)}}, k = 1,2,... \qquad \text{[Eq. 3-11]}$$

Now the remaining task is to find the function $f(d_i^{(0)},d_i^{(k)})$. It seems a good starting point to assume $f(d_i^{(0)},d_i^{(k)}) = 1$, i.e., all the airports share the same delay to operation elasticity, but this assumption ignores the fact that the traffic reduction is more when the delay is large. We have decided to take the following simple formula to incorporate this idea:

$$f(d_i^{(0)}, d_i^{(k)}) = 1 + \theta \, ?(\frac{d_i^{(k)}}{D^{(k)}} - 1), k = 1,2,... \qquad \text{[Eq. 3-12]}$$

where $D^{(k)}$ is the system average of per flight delay. One can see that $f(d_i^{(0)}, d_i^{(k)}) = 1$, when $d_i^{(k)} = D^{(k)}$. Under this model of delay to operation elasticity, the bigger the value of θ, the bigger the discrepancy among the airport delay to operation elasticities. Obviously, the best value for θ is the one that will give the largest constrained traffic. Our numerical experiments show that the constrained traffic forecast is not very sensitive to the value selected, and our final selection of θ is 1.0.

Absent an economic model to adjust the GA traffic, we assume the GA traffic-reduction distribution model follows the commercial traffic-reduction distribution model:

$$s_i^{(k)} = s_i^{(k-1)} - \beta_i^{(k)} \, ?\%\Delta d_i^{(k)}, k = 1,2,... \qquad \text{[Eq. 3-13]}$$

where

$$\beta_i^{(k)} = \gamma \, ?\alpha_i^{(k)}, k = 1,2,... \qquad \text{[Eq. 3-14]}$$

and γ is a constant. We used $\gamma = 1$ in this study, assuming that delay has the same elasticity for commercial and GA operations.

Since this a numerical process, we have imposed the following conditions during each iteration:

$$0 \le t_i^{(k)} \le t_i^{(0)},$$

$$-1.0 \le s_i^{(k)} \le s_i^{(0)}, k = 1,2,..., \qquad \text{[Eq. 3-15]}$$

and

$$t_i^{(k)}[j] \le t_i^{(k)}[j+1], k = 1,2,..., \qquad \text{[Eq. 3-16]}$$

where *j* is the index of the target year. The first condition states that the commercial operation growth rate at any target year must be between zero and the unconstrained growth rate. The second condition states that the GA operation growth rate at any target year must be between –100 percent and the unconstrained growth rate. The reason that the conditions for GA is different is because the unconstrained GA growth rates are negative for some airports. Since the growth rates in this study are always defined as the growth rates from the current year (1997) to the target year, the third condition states that there cannot be any negative commercial operation growth rates. The last condition does not hold for the GA, again, because of possible negative GA growth at some airports.

The following smoothing algorithm is employed to ensure a stable solution and quick convergence. Once $t_i^{(k)}$ and $s_i^{(k)}$ are computed, they have to undergo the following:

$$\begin{aligned} t_i^{(k)} &= \phi \; ?t_i^{(k)} + (1-\phi) \; ?t_i^{(k-1)} \\ s_i^{(k)} &= \phi \; ?s_i^{(k)} + (1-\phi) \; ?s_i^{(k-1)}, k = 1,2,... \end{aligned} \qquad \text{[Eq. 3-17]}$$

where ϕ is the smoothing constant. For all the scenarios, we picked $\phi = 0.2$. The smoothing constant is chosen to gradually change the operations growth rates so that we will not unduly cut the traffic too much at some airports that cannot be recovered later. Another benefit of the smoothing algorithm is that it drastically improves the speed of convergence to reduce the natural oscillation of this nonlinear network. Together with the next technique, we can improve the converging speed 10-fold.

While the smoothing algorithm speeds up the convergence at the beginning of the iteration process, it actually slows down the convergence when traffic estimates from the two models are increasingly close. The reason is that when they are close, using Equation 3-1 to update the traffic becomes quite precise but such change accounts for only about a 20 percent adjustment if the smoothing constant is 0.2. The way that we speed up the convergence is to stretch the initial estimate of $\alpha_i^{(k)}$ after Equation 3-11,

$$\alpha_i^{(k)} = \varsigma \; ?\alpha_i^{(k)}, k = 1,2,... \qquad \text{[Eq. 3-18]}$$

By experiment, we choose the stretcher ς to be 8.0 for the target year 2005, 4.0 for the target year 2010, and 2.0 for the target year 2015. The use of stretchers and their values have little impact on the final solution by our numerical experiments. Actually, stretcher is a common technique in numerical solutions because the initial estimation of $\alpha_i^{(k)}$ gives us the direction of the next step, and the stretcher modifies the step size.

The system stops iteration when the difference between the traffic of the two models is within a range of 0.1 percent. The final result is a revised TAF for both commercial and GA traffic, which explicitly accounts for air traffic congestion and the air carriers strategies to mitigate the total impact. More specifically, the methodology can be used to evaluate each operating strategy in isolation and to examine a combination of strategies. The next section describes the operating strategies that we were requested to study.

FUTURE OPERATING STRATEGIES

To accommodate increasing demand in the face of growing congestion, it is likely that air carriers will alter their current operating strategies. This section lists the possible airline strategies, discusses the methods we used to evaluate each strategy, and summarizes the likely consequences of each. The strategies involve the way air carriers will accommodate growth:

- by increasing fares and rationing demand in the face of scarce capacity (a passive strategy);
- by establishing new hub airports to mitigate congestion at existing hub airports;
- by shifting additional resources toward direct service as opposed to connecting service to mitigate congestion at major hub airports;
- by smoothing the peaks and valleys of typical bank operations to mitigate the growth of delay at major hub airports;
- by shifting additional resources toward nighttime operations;
- by employing larger aircraft, as opposed to growth in frequency; or
- through a combination of the five active strategies.

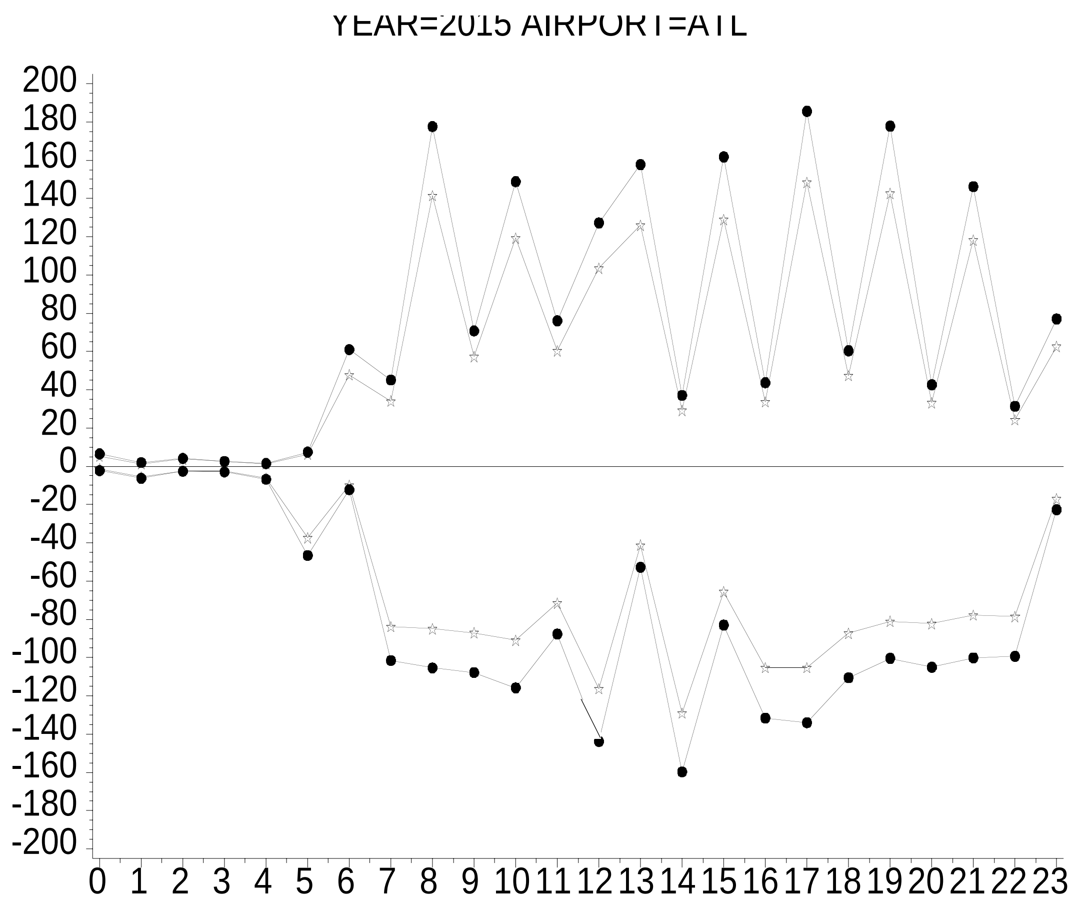
Fare Increase

The main premise of the increased fare strategy is that air carriers will use higher ticket prices to ration scarce capacity to its most valuable use. Thus, the projected growth in demand will not be fully accommodated as some travelers are priced out of the market. Although it is possible to implement this strategy in isolation, our view is that higher fares will be used in conjunction with other strategies to eliminate any residual discrepancies between demand and capacity.

As shown in Figure 3-1, the implementation of the increased fare strategy requires a link between the outputs of the Operations Model and the input of the ACIM. That link is accomplished by passing estimates of delay per flight from the Operations Model to the ACIM. Intuitively, the ACIM imposes the cost of the estimated delay on the air carriers and allows fare yields to increase correspondingly under the assumption that the industry will continue to be cost-competitive and must remain profitable to attract and retain capital. The fare yield changes are passed to the ACIM demand model, which estimates the corresponding reduction in passenger air travel demand according to price-elasticity parameters.

As shown in Figure 3-2, the high fare scenario depresses the traffic growth rates resulting in approximately the same demand pattern as in the unconstrained forecast.

Figure 3-2. Comparison Of Airport Operations at ATL For The Year 2015



Legend
• Unconstrained * High fare
Positive curve: departure Negative curve: arrival

Table 3-3 shows the impact of the higher fare scenario relative to the unconstrained (FCM-derived) forecast. In 2015, RPMs demanded and delivered under the higher fares scenario are 92.6 percent of the unconstrained forecast; nearly 100 billion RPMs are lost.

Table 3-3. Higher Fares Results (Billions Of RPMs)

Year	Higher fares	Unconstrained forecast
2005	828.0	843.6
2010	1,016.9	1,060.6
2015	1,233.5	1,331.4

New Hubs

The main premise of the new hub strategy is that air carriers will continue to utilize the hub-and-spoke-operating concept to meet the projected demand growth by establishing new hub cities to relieve congestion at existing hub airports. This strategy has the advantage of enabling the carriers to continue to adopt the proven efficiency of the hub-and-spoke mechanism but also meet the projected growth with minimal delay. However, new hubs require a significant portion of local travel to be economically viable. This is a difficult hurdle and may be hard to satisfy outside the largest metropolitan areas (which tend to be hub airports already). Also complicating this scenario is the need for a geographic location that compliments the existing hub airports of the major carrier. However, as traffic congestion continues to increase at existing hub airports, the attractiveness of new hubs also will increase.

Operationally, the new hub strategy is implemented through modification of the TAF. First, we identify a set of cities to develop as new hub airports. Once the set of new hub airports is identified, we increase the number of operations at the new hub airports and correspondingly decrease the number of operations at existing hub airports. It is important to recognize that although the identification of new hub cities is highly speculative, the aggregate results depend very little on the specific cities selected.

To categorize the 64 LMINET airports, we used Department of Transportation (DOT) origin and destination (O&D) data combined with DOT T-3 airport data. Specifically, we took the ratio of O&D enplaned passengers to T-3 enplaned passengers. This ratio shows the degree to which passengers are beginning or ending their air travel at an airport, or simply passing through enroute to some final destination. In 1995, this ratio ranged from a low of 0.19 (indicating a hub airport) to a high of 0.99 (indicating a spoke airport).

We broke the 64 LMINET airports into three categories based upon the O&D to T-3 ratio: current hub airports (A), potential hub airports (B), and spoke airports (C).[6] The results are as shown in Table 3-4.

Table 3-4. Hub Airport Categories

Category	Description	Airports
A	Current hub airports	ATL, CLT, CVG, DEN, DFW, DTW, EWR, IAD, IAH, JFK, LAX, MEM, MIA, MSP, ORD, PHL, PHX, PIT, SFO, SLC, and STL
B	Potential hub airports	ABQ, BNA, BWI, CLE, CMH, DAL, FLL, GSO, HOU, IND, LAS, MCI, MCO, MDW, MSY, OAK, PDX, RDU, SAN, SEA, and TPA
C	Spoke airports	AUS, BDL, BOS, BUR, DAY, DCA, ELP, HPN, ISP, LGA, LGB, MKE, ONT, PBI, RNO, SAT, SDF, SJC, SMF, SNA, SYR, and TEB

For each of the active airline strategies (as opposed to the passive strategy of passing delay costs to the traveling public in the form of higher airfares), we designated a low-end and a high-end for what we believed was a plausible range of scenario variables. To reflect the shift of operations from current hub airports to potential hub airports, operations at category-A airports were reduced by 1 percent, 2 percent, and 3 percent in 2005, 2010, and 2015, respectively for the low-end of the new hubs scenario. For the high-end , operations at category-A airports were reduced by 2 percent, 4 percent, and 6 percent in 2005, 2010, and 2015, respectively. To compensate for the reductions at current hub airports and maintain system-wide levels of RPMs delivered, operations at category-B airports were increased by 2.5 percent, 5 percent, and 7.5 percent for the low-end and by 5 percent, 10 percent, and 15 percent for the high-end. The results of the new hubs strategy are shown in Table 3-5.

Table 3-5. New Hubs Results (Billions of RPMs)

Year	Low	High
2005	829.0	829.6
2010	1,019.1	1,020.9
2015	1,237.8	1,241.4

Direct Service

The main premise of the direct service strategy is that air carriers will shift resources toward direct service to avoid some of the effects of congestion at major hub airports. Under this strategy, the proportion of passengers who travel directly

[6] Some exceptions to the strict numerical sorting were made. GSO and EWR were switched. BOS, DCA, ELP, and LGA were switched with IND, MDW, OAK, and SAN.

between their origination and destination, without making a connection, will continue to increase.

As in the schedule smoothing strategy, it must be recognized that the hub-and-spoke operation provides substantial economic benefits to the airline and its passengers relative to direct service. These benefits include higher frequency between any two cities, the economy of larger aircraft equipment, and the revenue enhancement from higher load factors. However, as congestion at major hub airports continues to increase, a tradeoff develops between the economies offered by hub-and-spoke operations and the diseconomies associated with delay. We believe that, in light of this tradeoff, it is unlikely that the major carriers will completely abandon the hub-and-spoke operating strategy. Therefore, the direct service strategy we propose represents an incremental departure from hub-and-spoke with some growth accommodated via direct service. Thus, our scenario preserves the hub-and-spoke-operating concept, but modestly reduces its role in accommodating future growth.

Operationally, the growth in direct service is accomplished through modification of the TAF. We began by analyzing Department of Transportation origin and destination (O&D) for 1995. From the O&D data, we made a preliminary sorting of airports based upon the proportion of travelers who experienced two or more legs in traveling from their origin to destination. Airports whose travelers had a high proportion of non-direct flights were categorized as “A”, those with a moderate proportion were “B”, and those with the lowest proportion were “C”. Table 3-6 shows the categories.

Table 3-6. Direct Service Categories

Direct service category	Description	Airports
A	High proportion of non-direct flights	ABQ, AUS, BDL, BOS, BWI, DCA, LAS, LAX, LGA, MCI, MCO, MKE, MSY, PHL, SAN, SAT, SDF, SEA, SFO, and TPA
B	Moderate proportion of non-direct flights	ATL, BNA, CLE, CMH, DAY, DEN, DTW, EWR, FLL, IND, MIA, ONT, ORD, PBI, PDX, PHX, RDU, SJC, SLC, SNA, and SYR
C	Low proportion of non-direct flights	BUR, CLT, CVG, DAL, DFW, ELP, GSO, HOU, HPN, IAD, IAH, ISP, JFK, LBG, MDW, MEM, MSP, OAK, PIT, RNO, SMF, STL, and TEB

We refined our initial screening by examining the O&D data at the airport-to-airport level and specifying a minimum threshold of 30,000 passengers per year not currently traveling non-stop to make the added direct flights economically viable. The threshold of 30,000 passengers per year is essentially 100 passengers per day, six days per week. The market opportunity is as shown in Table 3-7.

Table 3-7. Market Opportunity in 1995 (passenger trips)

Category	A	B	C	Destination
A	9,427,669	3,995,821	592,242	14,015,732
B	4,165,983	1,146,198	137,824	5,450,004
C	607,110	72,870	0	679,980
Origin	14,200,761	5,214,889	730,066	20,145,716

Dividing the average of the sums for the category as an origin and the category as a destination into the numbers of domestic O&D passengers within the category yielded the following proportions for categories A, B, and C, respectively: 12.31 percent, 5.38 percent, and 1.06 percent. These are the proportions by which we increase the numbers of operations within the three categories in 2015 for the high-end. The increases in 2005 and 2010 were a third and two-thirds of the final increase.

To account for the increased proportion of direct flights, we also reduced operations at the hub airports (defined in the previous section) by 1 percent, 2 percent, and 3 percent in 2005, 2010, and 2015, respectively. Essentially for every three new direct flights introduced, one hubbing flight was eliminated. This was done to avoid drastically reducing system-wide load factors. Taking both the increase in direct flights and the reduction in flights at hub airports into account, the system-wide number of operations increased by 0.8 percent, 1.7 percent, and 2.5 percent in 2005, 2010, and 2015, respectively.

For the low-end, operations in 2015 were increased by 6.16 percent, 2.69 percent, and 0.53 percent at category A, B, and C airports, respectively, and we reduced operations at the hub airports by 0.5 percent, 1 percent, and 1.5 percent in 2005, 2010, and 2015, respectively.

In terms of timing and penetration, the direct service strategy could be implemented by carriers in the near term. In fact, one can make a strong argument that direct service is already becoming an important business strategy for the major carriers. For example, the introduction of the regional jet may provide an opportunity to schedule frequent direct service in smaller markets. However, the fleet mix requirements to optimize the benefits of more direct service may take some time to realize. The results of the direct service strategy are shown in Table 3-8.

Table 3-8. Direct Service Results (Billions of RPMs)

Year	Low	High
2005	829.5	830.5
2010	1,020.3	1,023.2
2015	1,239.4	1,244.5

Schedule Smoothing

The premise of the schedule smoothing strategy is that air carriers can reduce the level of congestion at hub airports by smoothing the peaks and valleys associated with bank operations. Schedule smoothing is accomplished in the Operations Model by comparing the demand and the capacity of an epoch to determine the excessive demand that we want to spread or the extra capacity that we can use to take the spread demand from the neighboring epoch. Our earlier analysis relating average delays to on-time probabilities has shown that air carriers can tolerate approximately 3 to 4 minutes of unexpected delay [16]. In reality, the tolerance for delay is more a function of the variance of delay rather than the mean of delay. However, if the distribution of delays is exponential, which is the model we have tested and assumed, then its distribution, including its variance, is uniquely determined by the mean.

In our capacity function, the airport arrival/departure capacities in an epoch are determined by the arrival/departure demands, queues at the end of last epoch, and the current system state. Thus, excessive demand or extra capacity is also a function of how the airport is intended to be operated during the next epoch and how it has been operated to serve the demand. Through numerical experiment, we estimate that the capacity utilization ratio is between 90 percent and 95 percent among the airports to satisfy 3 to 4 minutes of average delay [16]. Thus, the excessive demand and extra capacity are estimated as follows:

If *demand – 0.95*maximum_capacity > 0,*

then *excessive_demand =demand – 0.95*maximum_capacity*.

If *demand – 0.95*maximum_capacity < 0,*

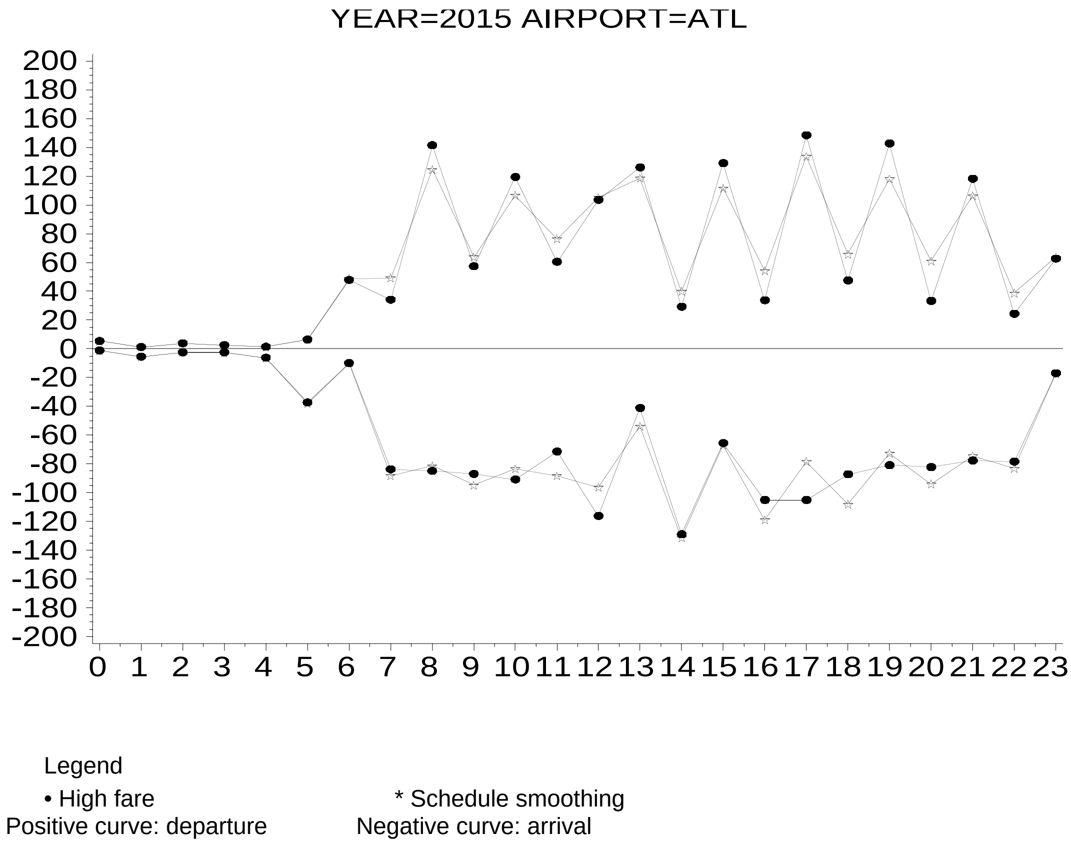
then *extra_capacity = 0.95*maximum_capacity – demand*.

In implementing the low-end of the plausible range for this scenario, we spread excessive demand in an epoch only to its immediately adjacent epochs, which will result in a schedule change to some flights by a maximum of 1 hour. This shift of flight schedule will result in a reduction of traveling passengers if the original schedule is optimal, which will further imply a reduction of operations [33]. However, the possible operation reduction is not considered significant because of the small time shift of the schedule, which is also compensated by the overall demand increase throughout the day. For the high-end, flights were allowed to move a maximum of 2 hours.

When implementing this scenario, we adhere to the following policies: (1) the spread of demand to the neighboring epochs cannot exceed the extra capacities of the neighboring epochs; and (2) the spread of demand in the neighboring epochs is proportional to their extra capacities.

One can see that this operation strategy works best to alleviate congestion when hourly demands exceed capacities alternately. This strategy does not help when demands exceed hourly capacities for long periods even though daily demand exhibits the peak-and-valley pattern.

Figure 3-3. Comparison of the Airport Operations in ATL for Year 2015



In Figure 3-3, the example of ATL for 1 hour smoothing indicates that the airport operations under the schedule smoothing scenario is just slightly different from the default (high fare) scenario. As a matter of fact, many airports in our 64 LMINET airports have almost identical airport operations under both the default and schedule smoothing scenarios. To understand this, one has to keep in mind that the excessive demand can be spread only to the neighboring periods. Therefore, smoothing has no effect if demand is consistently below capacity or above capacity, the latter of which is the case for many airports in the future.

It is also interesting to notice from information presented in Appendix D that smoothing has about the same effect on ATL for all the future target years considered. ATL is currently operated near its capacity, and it will be operated close to its capacity dictated by our algorithm to contain the delay growth. Thus, it is no surprise that the smoothing has almost the same effect to help the traffic growth to the future. Although smoothing could certainly help to accommodate future demand growth, caution must be exercised because tightly coupled bank operations provide tremendous value to the air carriers. To see this, note that as bank operations are stretched over a larger time period, the number of convenient connections declines rapidly. Thus, the costs of congestion induced by tightly coupled bank operations must be balanced against the benefits in terms of efficiency and connectivity. In addition, it must be considered that there is certainly a limit to which the schedule smoothing can be accomplished. Stretching a bank operation over more than 4 hours is not likely to yield much value to an airline or its passengers. Finally, there is no obvious reason why schedule smoothing could not begin to take place in the near term since the binding constraint would be the airline schedule, which can be easily adjusted into the future. Results of the schedule smoothing strategy are shown in Table 3-9.

Table 3-9. Schedule Smoothing Results (Billions of RPMs)

Year	Low	High
2005	831.5	833.0
2010	1,022.9	1,025.5
2015	1,242.7	1,248.4

Night Operations

The main premise of the night operations strategy is that air carriers will begin to shift some resources toward nighttime operations in order to meet projected demand growth without incurring unreasonable congestion. The basic idea is that as airports reach their arrival and/or departure capacities, the number of operations in those hours of the day will be effectively capped. Consequently, airlines will ration seats according to willingness to pay for flights that takeoff or land at the most desirable times of the day. This strategy implies that leisure travelers will be increasingly replaced by business travelers on flights that arrive or depart at the most congested hours.

Operations that exceed the arrival or departure ceilings in any hour will be candidates to move to the first available hour after 2100 and before 0600 that has unused capacity. However, not all flights will be moved one-for-one. The airlines may find it necessary to charge the displaced leisure travelers a higher fare in order to cover their marginal costs of providing the flight because high fare business travelers are not expected to the take night flights. Additionally, there is disutility for passengers associated with arrivals or departures during the nighttime, so that passengers will be expecting to pay lower, not higher, fees for travelling at night.. Significant use of nighttime flights can be expected when daytime leisure fares increase, due to increasing business demand, to the point where the nighttime flights are cheaper for the passenger than daytime flights.

In 1994, the ratio of typical business fares to the lowest discount fares was 2.53 to 1.0. The average flight in 1996 had a stage length of 707 miles and the average one-way fare paid was $91.20. Assuming a 40/60 mix between business and leisure travelers, this implies that the typical business fare on this average flight was $143.41 and the lowest discount fare was $56.75.

In 1996, airline direct operating costs were $42.35 per 1,000 available seat miles. Flight attendant expenses in the same year were $5.95 per 1,000 available seat miles and the typical flight delivered 115,118 available seat miles.

Consequently, direct operating costs[7] plus flight attendant expenses for the typical flight totaled $5,560. We make the value judgement that airlines would only offer nighttime fights that cover these costs of the flight. This assumption is less restrictive than requiring that the flight cover all of the airline's fixed plus variable costs.

Assuming a 65 percent load factor, the airlines would find it necessary to charge leisure travelers on nighttime flights an average fare of $52.48.[8] Regarding the disutility of flying at night, we use an increasing $10.00 per hour for departures and arrivals after 7:00 p.m. and before 8:00 a.m. for the low-end of the plausible range. For example, a flight that departs at 9:00 p.m. or 6:00 a.m. incurs an additional $20.00 non-monetary charge to reflect that this is an inconvenient time to travel. For the high-end, we use an increasing $5.00 per hour to reflect the disutility effect. If the price elasticity of demand for leisure travel is –1.2[9], demand will be reduced according to time of the day as shown in Table 3-10.

[7] Direct operating costs consist primarily of flight crew, fuel, maintenance, and aircraft depreciation and rental charges.

[8] The average aircraft in the commercial fleet had approximately 163 seats in 1996. Therefore, approximately 106 leisure travelers would be onboard the night-time flight.

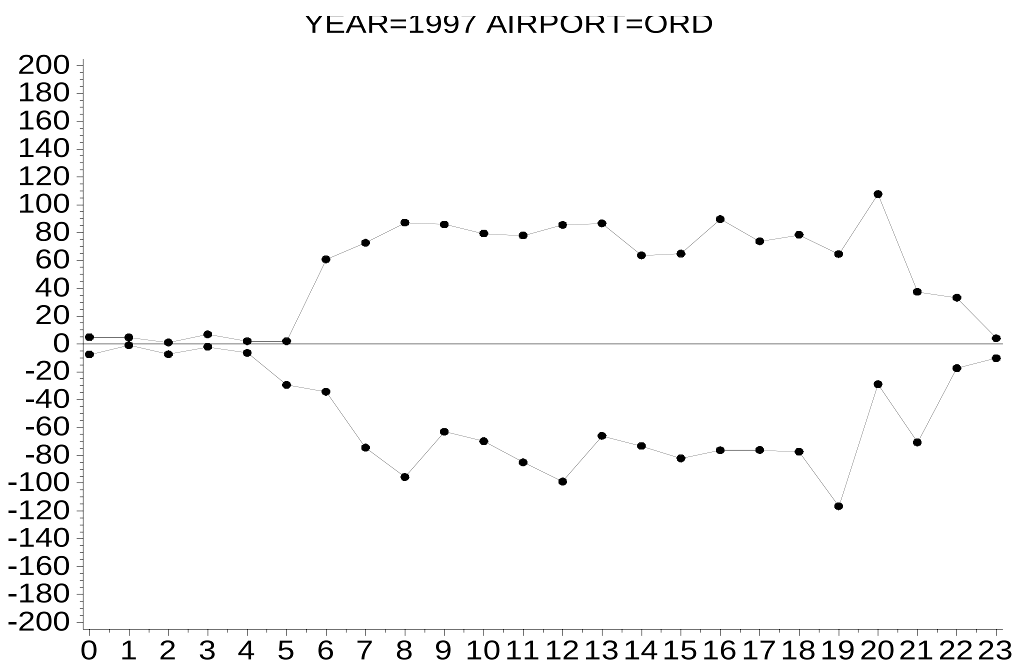
[9] Estimates of demand elasticities for air passenger leisure travel range between –0.4 and –1.98 [32]. Based upon our prior work, we believe that the overall price elasticity for air travel is –1.0, that business travel is price inelastic at –0.8, and that leisure travel is price elastic at –1.2.

Table 3-10. Nighttime Demand Reductions

Time	Night operations low	Night operations-high
2100	-33.3%	-12.1%
2200	-54.4%	-22.7%
2300	-75.6%	-33.3%
2400	-96.7%	-43.8%
0100	-100.0%	-54.4%
0200	-100.0%	-54.4%
0300	-96.7%	-43.8%
0400	-75.6%	-33.3%
0500	-54.4%	-22.7%
0600	-33.3%	-12.1%

This demand schedule matches quite well with airline and customer behavior at ORD (see Figure 3-4). Chicago O'Hare is slot controlled implying excess demand for air travel during the day and early evening. Despite the fact that there is excess capacity at night, and there are no current noise limitations on night flight, very few flights are observed during the period of 2400 to 0300 hours.

Figure 3-4. Airport Operations at ORD in 1997



Legend
Positive curve: departure Negative curve: arrival

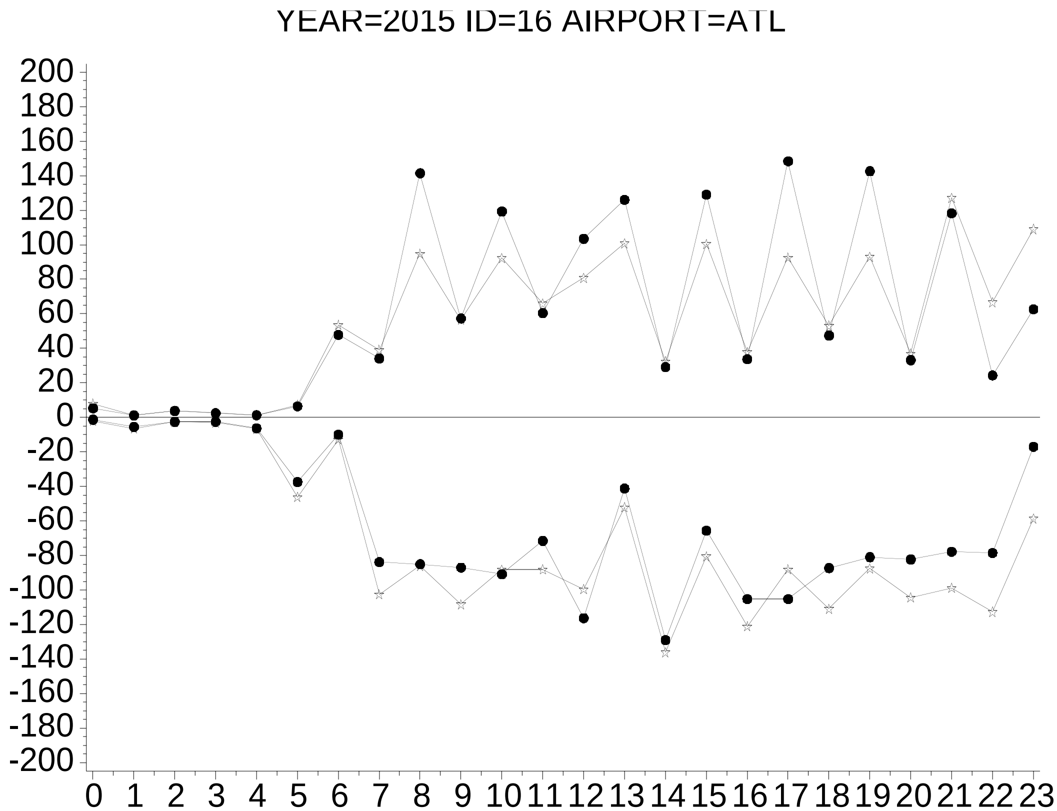
Finally, several airports place curfews on nighttime arrivals and/or departures. These airports and the restrictions imposed are shown in Table 3-11. For these airports, the hours available between 2100 and 0600 for nighttime operations were correspondingly limited.

Table 3-11. Nighttime Noise Restrictions

Airport	Comments
AUS	All operations voluntarily curtailed 2400 to 0600
DCA	2200 to 0700 curtailed unless less than 72 dBA on takeoff and less than 85 dBA on landing
HPN	All operations voluntarily curtailed 2400 to 0630
ISP	2300 to 0630 curtailed unless less than 72 dBA on takeoff and less than 85 dBA on landing
MSP	All operations voluntarily curtailed 2230 to 0600
PHL	Takeoffs prohibited 2300 to 0600
SAN	Takeoffs prohibited 2330 to 0630
SJC	All operations voluntarily curtailed 2330 to 0630
SNA	Takeoffs prohibited 2200 to 0700; landings prohibited 2300 to 0700

Figure 3-5 shows how operations at Atlanta are shifted from the most congested daytime hours to the less congested nighttime periods under the low-end range. Table 3-12 shows the results of the night operations strategy.

Figure 3-5. Comparison Of Airport Operations At ATL For The Year 2005



Legend

• High fare | * Night operations
Positive curve: departure | Negative curve: arrival

Table 3-12. Night Operations Results (Billions Of RPMs)

Year	Low	High
2005	832.2	833.2
2010	1,026.6	1,029.8
2015	1,253.6	1,262.1

Larger Aircraft

The premise of the larger aircraft strategy is that air carriers will begin to substitute larger aircraft equipment as landing slots become increasingly scarce, especially at the major hub airports. Historically, growth in air travel demand has been accommodated primarily through increases in the frequency of departures [18]. One consequence of congestion, however, is that continued growth in frequency may not be possible. Therefore, future growth in air travel demand would be accommodated with larger aircraft equipment.

To evaluate the impact of this strategy, we propose to modify the number of operations in the TAF to account for a higher ratio of RPMs per operation, for a given airport and year, served with larger aircraft. We propose to implement this modification across the board for all airports as opposed to specific airports only. The reason is that it would be highly speculative to project exactly which airports would benefit from the use of larger aircraft equipment and which would not. In addition, we expect that the annual change in average aircraft size will be a small incremental change from the unconstrained TAF. For the same reasons, we will not modify the traffic mix percentages in the airport capacity model.

In order to evaluate this strategy, we first had to estimate the number of RPMs that would be delivered at the various airports within LMINET. To do so, we started with DOT T-100 data at the airport level. We used 1995 data for numbers of RPMs and departures at each of the 64 airports. It should be emphasized that the T-100 data are for domestic operations performed by carriers that operate aircraft with more than 60 seats. Consequently, the ratio of RPMs to operations derived from these data are an approximation since international flights tend to use larger aircraft and fly longer stage lengths. Offsetting this is the exclusion of regional and commuter flights which typically use smaller aircraft and fly shorter stage lengths. Nevertheless, when the 1995 ratios of RPMs per operation were multiplied by the number of operations in 1997 at the LMINET airports, the resulting estimate of RPMs was 89.6 percent of the systemwide total. This seems quite plausible since 1997 enplanements at the 64 airports represented 84.9 percent of the systemwide total (see Table 2-2).

The airport-level figures of RPMs per operation were grown according to Tables 11 and 28 of the *FAA Aerospace Forecasts*. In 1997, the FAA systemwide ratio of RPMs to operations was 25,011. The comparable figures grow to 28,952, 31,902, and 35,150 in 2005, 2010, and 2015, respectively. A slight scaling was also necessary to grow the proportion of RPMs at the 64 airports relative to the total to 89.8 percent, 90.1 percent, and 90.4 percent in the three forecast years.[10] This is consistent with the growth in enplanements share shown in Table 2-2. The resulting airport-level figures, arranged by the intenal LMINET airport index, of RPMs per operation are shown in Table 3-13.

[10] The scaling factors are 0.9989, 1.0090, and 1.0284.

Table 3-13. Estimates of RPMs Per Operation

Airport code	1997 RPM/OPN	2005 RPM/OPN	2010 RPM/OPN	2015 RPM/OPN
ABQ	21,618	24,997	27,821	31,246
ATL	25,880	29,924	33,306	37,405
AUS	16,466	19,039	21,191	23,799
BDL	26,394	30,519	33,968	38,149
BNA	20,109	23,252	25,880	29,065
BOS	28,541	33,001	36,730	41,251
BUR	15,943	18,435	20,518	23,044
BWI	26,973	31,189	34,713	38,986
CLE	16,079	18,591	20,692	23,239
CLT	18,815	21,755	24,214	27,194
CMH	20,581	23,798	26,487	29,747
CVG	26,538	30,685	34,152	38,356
DAL	11,944	13,811	15,371	17,263
DAY	10,681	12,350	13,746	15,438
DCA	20,555	23,768	26,454	29,710
DEN	37,025	42,812	47,650	53,515
DFW	30,662	35,454	39,460	44,317
DTW	26,970	31,185	34,708	38,981
ELP	19,883	22,990	25,588	28,737
EWR	35,416	40,951	45,579	51,189
FLL	43,695	50,523	56,233	63,154
GSO	11,553	13,358	14,868	16,698
HOU	14,896	17,224	19,170	21,530
HPN	10,695	12,366	13,764	15,458
IAD	54,038	62,483	69,544	78,103
IAH	27,637	31,957	35,568	39,946
IND	22,076	25,526	28,410	31,907
ISP	21,371	24,711	27,503	30,888
JFK	78,017	90,210	100,403	112,762
LAS	36,741	42,483	47,283	53,103
LAX	59,384	68,665	76,424	85,831
LGA	25,693	29,709	33,066	37,136
LGB	15,034	17,384	19,348	21,730
MCI	24,515	28,346	31,550	35,433
MCO	43,545	50,350	56,039	62,937
MDW	20,961	24,236	26,975	30,295
MEM	22,104	25,558	28,446	31,947
MIA	48,152	55,678	61,969	69,597
MKE	17,163	19,845	22,088	24,806
MSP	34,669	40,087	44,617	50,109
MSY	21,998	25,436	28,311	31,795

Table 3-13. Estimates of RPMs Per Operation (Continued)

Airport code	1997 RPM/OPN	2005 RPM/OPN	2010 RPM/OPN	2015 RPM/OPN
OAK	20,443	23,637	26,309	29,547
ONT	24,183	27,963	31,123	34,953
ORD	35,076	40,558	45,141	50,697
OTR	5,689	6,842	7,792	8,979
PBI	37,249	43,071	47,938	53,838
PDX	25,735	29,757	33,120	37,197
PHL	27,031	31,256	34,787	39,069
PHX	34,682	40,102	44,633	50,127
PIT	20,799	24,049	26,767	30,061
RDU	17,574	20,321	22,617	25,401
RNO	23,789	27,507	30,615	34,384
SAN	35,903	41,514	46,206	51,893
SAT	19,678	22,754	25,325	28,442
SDF	11,875	13,730	15,282	17,163
SEA	42,103	48,683	54,184	60,854
SFO	69,328	80,163	89,222	100,204
SJC	29,979	34,664	38,581	43,330
SLC	39,638	45,832	51,011	57,290
SMF	28,394	32,832	36,542	41,040
SNA	36,925	42,696	47,521	53,370
STL	21,551	24,919	27,735	31,148
SYR	9,332	10,791	12,010	13,488
TEB	21,371	24,711	27,503	30,889
TPA	31,791	36,759	40,913	45,949

Generally, two types of needs drive aircraft acquisitions: acquisitions to replace retiring aircraft and acquisitions to meet additional growth. Thus, increases in average aircraft size can come from two sources. In aggregate terms, the unconstrained TAF projects a continuing upward drift in average aircraft size of approximately one seat per aircraft per year. We assume additional 0.5 percent and 1.0 percent per year increases in average seat-size of aircraft in the fleet. Because aircraft are long-lived assets, it is difficult to make large changes to fleet characteristics in a short period of time. However, small changes can be accommodated in fleet planning, as shown in Table 3-14.

Table 3-14. Fleet Composition Under Alternative Scenarios

Scenario	< 50 (%)	50-69 (%)	70-90 (%)	91-120 (%)	121-170 (%)	171-240 (%)	241-350 (%)	>350 (%)
Baseline, 1995	7.7	1.5	2.1	18.3	46.7	13.3	8.1	2.4
Baseline, 2015	5.9	1.1	1.6	14.0	40.4	29.0	6.2	1.8
Additional 0.5 percent increase, 2015	5.9	1.1	1.6	14.2	36.3	28.5	10.4	1.9
Additional 1.0 percent increase, 2015	6.0	1.1	1.7	14.4	36.9	15.1	22.8	1.9

Increases in average seats per aircraft will directly impact the RPM per operation figures. For example, if average seats per aircraft increase an additional 0.5 percent per year (above the 0.496 percent already assumed by the *FAA Aerospace Forecasts*), RPMs per operation in 2015 will be 9.39 percent higher than they would have been otherwise. Consequently, systemwide operations in 2015 would decline from 40.18 million to 36.73 million. Under the larger 1.0 percent increase, systemwide operations would decline further to 33.59 million in 2015.

Because of the extremely long life-cycle of existing aircraft and the significant lag between ordering new aircraft and receiving deliveries, this strategy is not likely to have a large impact in the near term. Rather the real impact of this strategy will be realized in the later years of our forecast period (2010 to 2015). Results of the larger aircraft strategy are shown in Table 3-15.

Table 3-15. Larger Aircraft Results (Billions of RPMs)

Year	Low	High
2005	832.9	837.4
2010	1,030.3	1,041.8
2015	1,264.6	1,290.5

Combinations of Five Active Strategies

We also considered combinations of the five active airline strategies. Keeping with our convention, we defined lower and upper bounds to the plausible range. A summary of the combinations of strategies is shown in Table 3-16.

Table 3-16. Combinations of Strategies

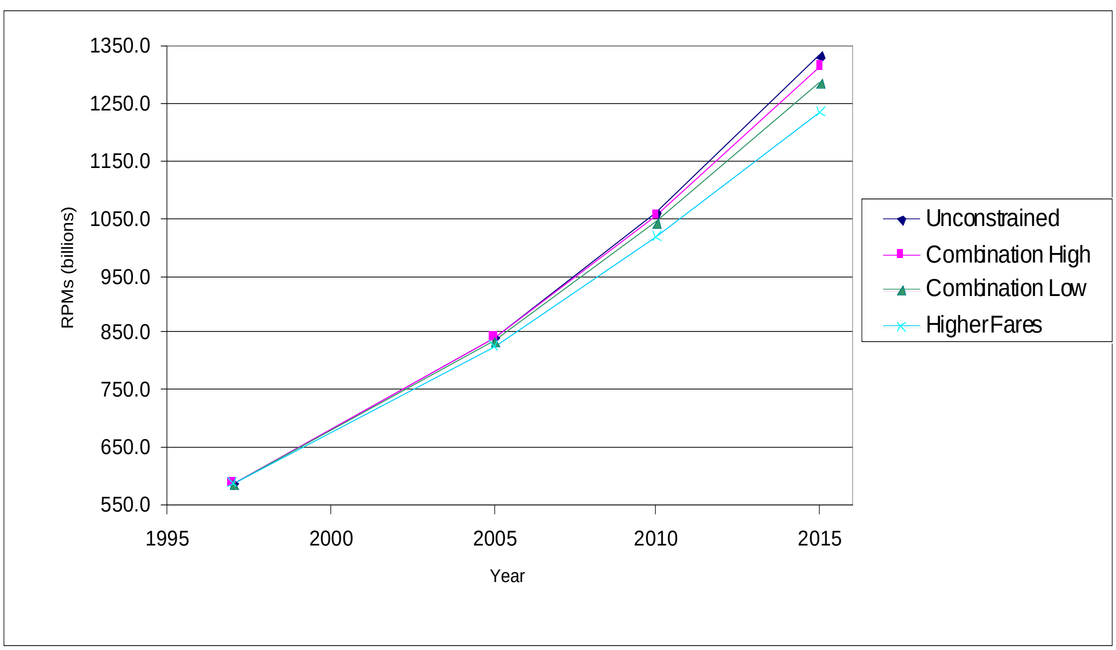
Business strategy	Low combination	High combination
New hubs	3 percent reduction at current hubs by 2015	6 percent reduction at current hubs by 2015
Direct service	6.16 percent increase at category A airports by 2015	12.31 percent increase at category A airports by 2015
Schedule smoothing	1-hour maximum spread from peak	2-hour maximum spread from peak
Night operations	Larger travel demand reduction at night	Smaller travel demand reduction at night
Larger aircraft	0.5 percent additional growth in average seats per aircraft	1.0 percent additional growth in average seats per aircraft

As shown in Table 3-17 and Figure 3-6, combinations of strategies are quite effective in delivering the RPMs demanded under the unconstrained forecast.

Table 3-17. Combination Results (Billions of RPMs)

Year	Higher fares	Low combination	High combination	Unconstrained forecast
2005	828.0	837.3	843.9	843.6
2010	1,016.9	1,041.8	1,055.0	1,060.6
2015	1,233.5	1,287.8	1,313.2	1,331.4

Figure 3-6. Combination Results



Industry Feedback

We briefed our methodology and preliminary results to members of Boeing's Commercial Airplane Group on June 23, 1999. Our briefing was generally well received and we obtained some excellent feedback from the Boeing staff. We examined, in detail, two strategy variants suggested by them.

The first strategy variant was to determine the degree to which RPMs delivered could be improved through larger shifts of operations from current hub airports to potential hub airports. As shown in Table 3-18, RPMs delivered in the years 2010 and 2015 are maximized by shifting between 9 percent and 12 percent of operations from the current hub airports. Beyond that point, however, RPMs delivered start to decline. Delay is reduced at the current hub airports but this is more than compensated for by an increase in delay at the potential hub airports as they increasingly bump up against their own capacity constraints.

Table 3-18. New Hubs Variant Results (BillionsOf RPMs)

Year	3% reduction	6% reduction	9% reduction	12% reduction	18% reduction	24% reduction
2005	829.0	829.6	830.4	830.8	831.4	831.6
2010	1,019.1	1,020.9	1,022.1	1,022.6	1,021.9	1,019.6
2015	1,237.8	1,241.4	1,243.6	1,243.9	1,238.2	1,228.0

The second strategy variant was to allow the average size of aircraft in the fleet to continue to follow its historic trend[11] out to the year 2005 and then begin either a 0.5 percent or 1.0 percent increase above that predicted by the FAA forecast. As shown in Table 3-19, if the airlines continue the historic trend toward smaller aircraft, this results in a considerable reduction in RPMs delivered relative to that hypothesized under the baseline larger aircraft strategy.

Table 3-19. Larger Aircraft Variant Results (Billions Of RPMs)

Year	Historic low	Historic high	Larger aircraft low	Larger aircraft high
2005	825.5	825.5	832.9	837.4
2010	1,016.4	1,021.5	1,030.3	1,041.8
2015	1,241.5	1,258.0	1,264.6	1,290.5

Delay Results

To a first approximation, system-wide delay is a function of the number of operations at the various LMINET airports. All other things being equal, more operations

[11] From 1983 to 1997, average seats per aircraft in the fleet declined from 167.1 to 159.2 according to FAA statistics. This is a compound annual change of –0.345 percent.

will tend to increase the total amount of delay. Other factors include whether additional operations occur at already busy airports or during already congested times of the day. In those instances, the delay impacts are magnified.

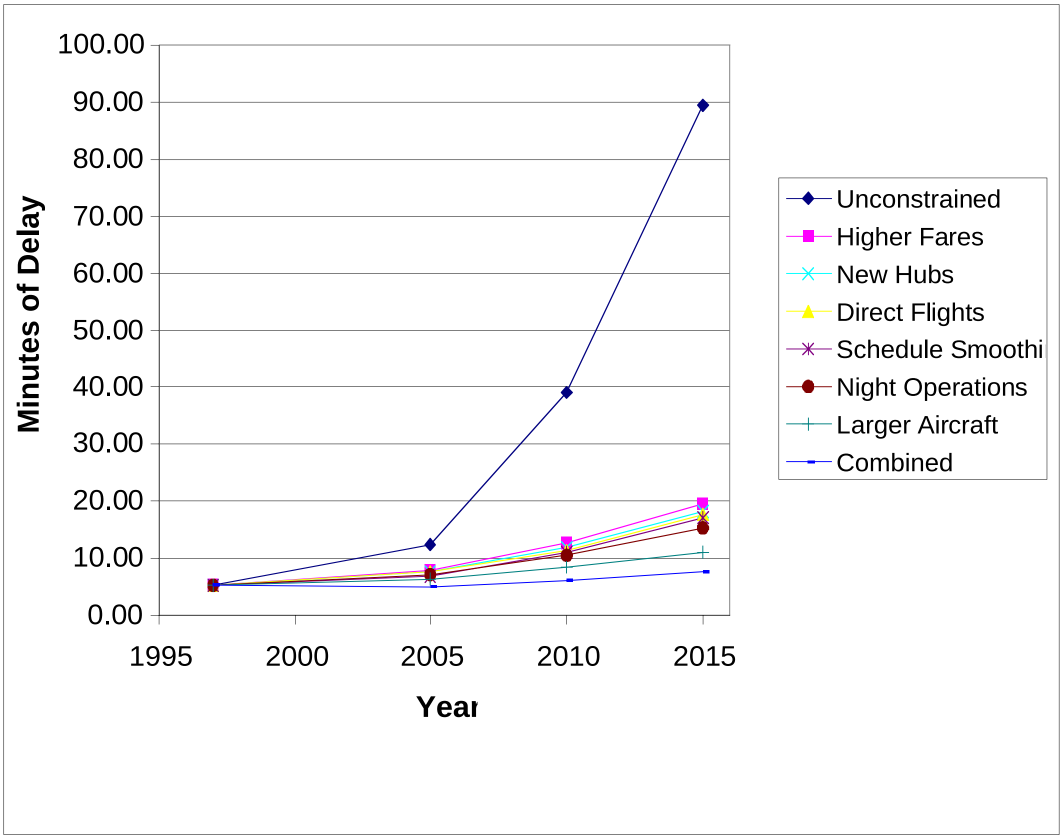
Table 3-20 and Figure 3-7 show average delays per flight according to the potential airline strategies and the unconstrained forecast. For the airline strategies, the worst system-wide delay is observed for the higher fares scenario where the airlines simply continue their current method of conducting business despite a large increase in operations demanded by forecast RPM growth. Delay costs simply are passed along to the traveling public in the form of higher fares. At the opposite end of the spectrum, delay is the least when the airlines follow a combination of active strategies. This is closely followed by the stand-alone strategy of incremental growth in average aircraft size (above that already incorporated into the FAA forecast). Night operations also are effective as a stand-alone strategy because airline departures and arrivals are moved from heavily congested times to the less busy evening period.

Table 3-20. Average Minutes Of Delay Per Operation

Scenarios	1997	2005		2010		2015	
		Low	High	Low	High	Low	High
Unconstrained	5.34		12.48		39.11		89.44
Higher fares	5.34		7.97		12.54		19.41
New hubs	5.34	7.80	7.67	12.16	11.85	18.78	18.24
Direct flights	5.34	7.71	7.52	11.92	11.39	18.53	17.76
Schedule smoothing	5.34	7.20	6.84	11.47	11.03	18.01	17.11
Night operations	5.34	7.20	7.03	10.95	10.43	16.49	15.18
Larger aircraft	5.34	7.08	6.26	10.32	8.43	14.71	10.96
Combined	5.34	6.29	4.90	8.31	6.10	11.37	7.75

The effects of the remaining three strategies on delay are very close. Schedule smoothing has a slight effect because the hours immediately surrounding peak arrival and departure times also tend to be very busy. Direct flights reduce average delays because operations at hub airports are somewhat reduced, although there is a slight net increase in system-wide operations (2.5 percent in 2015). “New hubs” appears to be the least effective strategy because the system-wide number of operations remain virtually unchanged, although operations are shifted from busy hub airports to less busy potential hub airports (but these airports may face their own capacity constraints).

Figure 3-7. Average Minutes of Delay Per Operation



CONCLUSIONS

The growth in operations explicit in the FAA's Terminal Air Forecast will result in increasingly high levels of delay as capacity constraints at key airports are approached. By the year 2015, our models predict that the average delay per operation under the FAA unconstrained forecast will be nearly 90 minutes. This is clearly not sustainable, and the airlines will have to take steps to reduce the impact of congestion.

We evaluated one passive strategy and five active strategies that the airlines might potentially adopt to deal with increasing levels of delay. The passive, "higher fares" strategy simply passes along delay costs to the traveling public in the form of higher ticket prices. In 2015, RPMs demanded and delivered under the higher fares scenario are 92.6 percent of the unconstrained forecast. The resultant reduction in operations reduces average delay per operation in 2015 to just under 20 minutes.

We also evaluated five active strategies; these are (in increasing order of projected effectiveness in satisfying the RPMs demanded under the unconstrained forecast): new hubs, more direct service, schedule smoothing, night operations, and larger aircraft. For each of these active strategies, we evaluated a plausible range of scenario variables. Finally, we combined all five active strategies under the assumption that small incremental steps would be less risky than pinning hopes on a single panacea. We expect that the eventual strategies followed by the airlines will approximate the effects of the low-end combination strategy. Under this scenario, 96.7 percent of the RPMs demanded in 2015 under the unconstrained forecast are delivered. Even under this relatively optimistic scenario, average delay per operation still increases by over 100 percent from the levels of 1997 and would be expected to increase further during the years beyond 2015.

It should be noted that our forecast is subject to considerable uncertainty, particularly with regard to when the airlines begin to increase the average size of aircraft in their fleets. All other factors being equal, a continuation of historic trends and a significant introduction of regional jets will tend to decrease the ratio of RPMs to operations and increase the amount of delay per aggregate level of RPMs demanded.

Chapter 4

Analysis Under New NAS Architecture

This chapter addresses the future NASA operations concept involving NAS architecture and ATM technologies. Note: This chapter is written without carrying out any numerical analysis outlined herein.

FUTURE NAS OPERATION CONCEPT

Future NAS Architecture

The "NAS architecture" is a plan by the FAA to transition the current system from primarily ground radar-based, limited flexibility operation to a one using modern technology, shared information, and a common data exchange system that will be safer and more user efficient. The information presented here is based upon information about the architecture plan, which has been an evolving product taking into account inputs from all NAS stakeholders [12].

According to the architecture plan, the modernization phases of NAS follow the concept and its implementation of *free flight*. Free flight will enable pilots to make dynamic changes to their routes, speeds, or altitudes that will optimize the fuel consumption of a flight. The separation of flights will be the responsibility of pilots, and ATC will intervene only in case of potential conflict.

The plan specifies three phases of the NAS modernization process listed as follows:

- *Phase 1 (1998-2002):* Begin NAS modernization and implement a limited free flight prototype.
- *Phase 2 (2003-2007):* Continue NAS modernization and begin transition to free flight.
- *Phase 3 (2008-2015):* Complete NAS modernization and begin free flight operations.

In addition to other benefits to achieve higher safety standards, one of the goals of the future NAS architecture is to maintain and enhance the current level of ATC service. Many concepts will make airlines and pilots operate in quite a different manner, but the general framework to conduct a flight operation will remain intact involving flight planning, airport surface operations, terminal area operations, and en-route operations. The goals and the implementation schedule by 2005, 2010, and 2015 in those areas are summarized in the following subsections.

- Data link services will reduce communications and read-back errors.
- Collaborative interaction between users and service providers will aid in mutually developing solutions to problems such as demand-capacity imbalances and adverse weather en-route, leading to a transition to temporary route structures to resolve short-term problems and enabling tailored responses to meet demand-capacity imbalances at airports.
- Modernization will streamline the flight planning process and increase user self-reliance for preflight services.
- Today's flight plan will be replaced by a more detailed flight profile, which in turn will be part of a larger data set called a flight object.
- Information on current and predicted weather conditions, traffic density, restrictions, and status of special usage airspaces (SUA) will be available to improve the efficiency of generating the flight profile.

<u>Current:</u>

- Functions engender minimal information sharing between user and service provider.
- The OAG arrival schedule is used as the baseline for the ground delay program, instead of the computed arrival time.

<u>By 2005:</u>

- Users will be allocated an aggregate number of arrivals within an arrival window, which allows the user to determine departure time needed to meet an arrival slot.
- Day-to-day variance reduction reduces scheduling delays, saves fuel and time, and increases flexible use of airspace capacity.
- Dynamic capacity adjustments enhance the NAS capability to handle adverse weather, traffic, or equipment-based air traffic delays.

<u>By 2010:</u>

- NAS-wide predictive corrective maintenance actions ensure a full operational capability of the NAS system.
- NAS 4D TFM planning enables flight planning based on predicted SUA schedules, weather, provider resources, and traffic congestion.

By 2015:

NAS-wide 4D TFM planning enables flight plan approval based on SUA activities, real-time weather, service provider resources, and the operational traffic situation.

AIRPORT SURFACE OPERATIONS

- NAS modernization will provide more efficient and safer surface operations for aircraft moving to and from the runway and terminal gates.
- Improved efficiency of low-visibility surface operations of both aircraft and ground vehicles, and taxi sequencing and spacing and will unfold.
- Improved weather and traffic situational awareness of all moving aircraft and vehicles in both the tower and cockpit will be achieved, aiding pilots in adhering to taxi instructions, allowing vehicle drivers to avoid active runways in low visibility, permitting taxi operations in lower runway visual range, and instantly notifying service providers of any possible runway incursions.
- Faster and more reliable user/provider communications will be realized.
- Increase in airport capacity and reduction in taxi delays will happen.
- Time and fuel savings resulting from taxi planning, improved ramp control, integrated surface traffic movement with departure and arrival activities, and reduction of time between de-icing operations and departures will occur.

TERMINAL AREA OPERATIONS

- NAS modernization will support more flexible use of terminal airspace and increase the number of available runways for IFR operations enabling more flexible routing and user-preferred trajectories to and from airport runways and monitoring of conformance with arrival and departure trajectories.
- A seamless digital communications network will facilitate coordination among tower, departure/arrival, and en-route service providers, while data link services will provide fast and reliable delivery of air traffic information, and an increased capacity in the communications between controllers and pilots (reducing the workload of controllers and pilots).
- Flexible low-altitude routes will offer reduced flight mileage, fuel consumption, and flight time.

- Preferential arrival and departure procedures will allow aircraft to use a greater portion of the airspace around the airports.

- Exact aircraft positions in relation to desired flight paths will result from an earth geo-coordinate system.

- Automated DSTs will integrate departures with arrivals. The ability to sequence and merge arrivals in accordance with user preferences will be realized. Service providers will be able to monitor compliance with arrival and departure paths throughout the terminal airspace. Users will receive the most expeditious routes to the airport as a result of new terminal procedures reducing the number of vectors to an airport; therefore, aircraft will have greater arrival and departure flexibility.

- Allowing pilots to maintain aircraft-to-aircraft separation during instrument weather conditions will be possible during certain situations. Approach and departure spacing will be conducted by users in both visual and instrument weather conditions.

- Simultaneous approaches to closely spaced parallel runways will increase airport capacity during normal and instrument weather conditions, increased efficiency in approaches and departures will lead to more efficient runway use. Reduced congestion will result in reduced operational deviations and error.

- The current 250-knot speed restriction below 10,000 feet will be eliminated, thus allowing departing aircraft to fly optimal angle of attack climb profiles while arriving aircraft will be able to remain at higher altitude and begin their descents closer to the airport, both resulting in more efficient fuel consumption and noise reduction around airports.

- An increase in the number of satellite precision approaches at certified airports covered in the GPS augmentation area, as well as an increase in the number of instrument precision approaches at certified airports will be realized.

- The ability to provide instrument approaches with vertical guidance to many airports that do not currently have instrument approaches will occur. This will relieve some traffic congestion at major hub airports during IFR operations, expanding capacity, and enable more efficient use of airport assets. Increased service to a greater number of regional airports will result from the availability of precision approaches.

<u>Current:</u>

- An initial data link reduces problems of overlapping transmissions and ambiguities in pilot-controller communications and increases the timeliness of message delivery for pre-departure clearances.

- Improved arrival departure procedures reduce take-off and landing delays due to more timely information in the cockpit for departure and arrival sequencing.

By 2005:

- Better initial sequencing spacing provides orderly flow to airport, increasing runway acceptance rate, and reducing arrival and departure delays.
- Low-altitude direct improved airport access, resulting in direct terminal routes, will benefit low-performance aircraft, separating them from high-performance jets, while decreasing miles flown, flight times, and fuel consumption.
- Initial shared responsibility provides limited cockpit assumption of separation responsibility during designated situations.

By 2010:

- New low-visibility surface operations technology provides pilots and controllers with situational awareness that enables low/obscured-visibility taxi operations.
- Low/no-visibility surface operations are possible through the use of LAAS, moving map display, Stop-Bar, and sequencing taxi lights, which provide more accurate information and improved orientation for taxiing.

By 2015:

- ADS position data processing, real-time communications, and increased decision support will enable equal visual flight rule/instrument flight rule (VFR/IFR) air traffic acceptance rates.

EN-ROUTE OPERATIONS

- Separation standards will be reduced, and pilots will be able to conduct self-separation operations, as a result of both increased situational awareness in the cockpit and on the ground and of technologies that enhance the existing collision-avoidance systems.
- DSSs will ensure positive separation of aircraft, while allowing maximum aircraft performance and flight path flexibility.
- Structuring of airspace and reductions in current boundary restrictions will be more flexible.

- The airspace structure will be evaluated and adjusted to handle the demands of traffic flow or in response to weather conditions or NAS operational restrictions.

Current:

- The current national route structure, consisting of Victor airways and jet routes.

- More efficient route and altitude usage provides flexible route and altitude flight profile optimization.

By 2005:

- Better strategic route and altitude planning enhances NAS flexibility during adverse weather conditions, traffic congestion, or service provider resource limitations during peak operational periods.

- Reduction in daily variance reduces scheduling delays, saves fuel and time, and increases flexible use of airspace capacity.

- Increase in dynamic routes and altitudes provides flexible, near real-time adjustments to routes and altitudes.

By 2010:

- Reduced separation standards enhance system capacity and efficiency.

- Seamless cruise results in common en-route and oceanic infrastructure standard procedures and provides flexible and more efficient use of airspace.

By 2015:

Free flight in low-density areas provides flexible route and altitude selection with minimal service provider constraints.

NASA-Sponsored ATM Technologies

The Terminal Area Productivity (TAP) and Advanced Aviation Transportation Technologies (AATT) are the two NASA-sponsored programs that we have identified that will improve future NAS operations [15].

Terminal Area Productivity

The goal of TAP is to safely achieve clear-weather capacity in instrument-weather conditions. Realizing this goal will provide the following benefits:

- safely reduce aircraft spacing in the terminal area;
- improve low-visibility landing and surface operations, reduce runway occupancy, times and increase taxi speeds in low-visibility conditions; and
- safely reduce the required runway separation for independent, multiple-runway operations conducted under instrument flight rules.

All TAP technologies are slated to be implemented by the year of 2005. However, certain dependencies exist for many of the TAP technologies to be implemented. Management decisions and program scheduling could significantly affect the dates of TAP technology implementations. The successful implementation of the AVOSS and DROM technologies are dependent primarily on the efforts of the FAA. Alternatively, the successful implementation of technologies, such as LVLASO, ATM-1, and ATM-2, depend on the efforts and coordination of both the FAA and the airlines. Each of these technologies requires data links in addition to some other new equipment and controller and pilot procedures. Thus, the implementation schedule of the TAP technologies seems to be very debatable.

Advanced Air Transportation Technologies

AATT will provide benefits in the operational areas described in the next subsections [28].

Flight Planning

The cockpit-based Airborne Planner for Avoiding Traffic Hazards (APATH) provides strategic flight planning/user-preferred trajectory generation, cockpit-based conflict detection and resolution, and display capabilities for pilots to perform in-flight replanning. This ability enables the avoidance of traffic, hazardous weather, turbulence, terrain, SUA, and congested airspace.

Surface Movement Operations

Improved surface operations will be realized as the AATT implements several decision support tools. As ATCT controllers and supervisors, AOC dispatchers, and airport ramp operators are assisted by DSTs, they will be able to monitor and predict future air traffic surface movements, thus enabling more efficient surface operations. This capability will provide a decrease in average taxi delay time. As additional arrival and departure aircraft status and prediction information from the terminal ATC automation becomes available over time, additional capabilities will be realized, such as improved situational awareness of the flight deck, ATCT controllers and supervisors, AOC dispatchers, and airport ramp operators. These capabilities will enable more efficient surface operations. Also, TRACON controllers will be assisted in providing efficient terminal departure aircraft schedules, sequences, departure gate balancing, and en-route fix merging. TRACON "final" approach controllers will be assisted in maximizing airport arrival throughput by providing efficient terminal arrival aircraft speed and heading advisories. A collaborative decision-making environment that utilizes the air traffic trajectory predictions capabilities of CTAS for improved fleet management decisions, improved ATC clearances, and more efficient aircraft arrival trajectories into congested hub airports, will be facilitated by AOC-ATM information exchange. Situation visualization in the cockpit will facilitate interaction between the pilot and the ATM.

The AATT products supporting surface movement operations are Passive Surface Movement Advisor (PSMA) or SMA-1, Enhanced Surface Movement Advisor (ESMA) or SMA-2, Expedite Departure Tool (EDP), Active Final Approach Spacing Tool (A-FAST), Collaborative Arrival Planning (CAP), and Airborne Planner for Avoiding Traffic Hazards (APATH).

Terminal Area Operations

Terminal area operations improvements are addressed by several of the AATT products. ARTCC TMCs and ARTCC arrival sector controllers are assisted in the efficient sequencing and spacing of en-route, arriving air traffic over meter fixes. TRACON TMCs are assisted in sector staffing planning and setting efficient traffic flow management parameters, such as runway and airport acceptance rates. TRACON approach controllers are assisted in the "feeder," "final," and TMU positions in providing efficient terminal arrival aircraft schedules, sequences, and runway assignments. TRACON "final" approach controllers will be assisted in maximizing airport arrival throughput by providing efficient terminal arrival aircraft speed and heading advisories. TRACON controllers will be assisted in providing efficient terminal departure aircraft schedules, sequences, departure gate balancing, and en-route fix merging. A collaborative decision-making environment that utilizes the air traffic trajectory predictions capabilities of CTAS for improved fleet management decisions, improved ATC clearances, and more efficient aircraft arrival trajectories into congested hub airports will be facilitated by AOC-ATM information exchange. ARTCC sector controllers will be assisted in issuing inter-sector, cost-effective conflict resolution advisories, and issuing conflict-free, movement clearances that comply with traffic flow restrictions. ARTCC sector controller workload will be reduced through automatic conflict-resolution advisories. ARTCC controllers will be provided traffic flow management plan coordination across adjacent ATRCC facilities. ARTCC controllers and airspace users will be assisted in facilitating collaborative rerouting around hazardous weather and SUA. Tools also will assist in automated CTAS/FMS trajectory negotiation.

The AATT products supporting terminal area operations are Traffic Management Advisor (TMA), Passive Final Approach Spacing Tool (P-FAST), A-FAST, EDP, CAP, CTAS, Area and Sector Tool (AT/ST), and Advanced En-Route Ground Automation (AERGA).

En-Route Operations

Future en-route operations concepts also are addressed by AATT products. ARTCC controllers will be assisted in detecting future aircraft conflicts, in developing conflict-free resolution advisories, in issuing inter-sector, cost-effective conflict-resolution advisories, in generating advisories to enable efficient air traffic descents into terminal airspace and compliance with miles-in-trail traffic flow management constraints, and in issuing conflict-free movement clearances that comply with traffic flow restrictions. ARTCC sector controller workload will be reduced through automatic conflict-resolution advisories. ARTCC controllers will be provided traffic flow management plan coordination across adjacent ATRCC facilities. ARTCC controllers and airspace users will be assisted in facilitating collaborative rerouting around hazardous weather and SUA. Tools also will assist in automated CTAS/FMS trajectory negotiation. The advanced integrated flight deck will enable the pilot to interact with the dispatcher and controllers in planning and implementing user-preferred trajectories.

The AATT tools supporting en-route applications are conflict Prediction and Trial Planning (CPTP), AT/ST, AERGA, and Airborne Planner for Avoiding Traffic and Hazard (APTATH).

The implementation schedule of the AATT tools is as follows:

- By 2000: TMA (2000).
- By 2005: P-FAST (2001), SMA-1 (2001), CPTP (2002), SMA-2 (2003), and AT/ST (2004).
- By 2010: EDP (2006), A-FAST (2006), CAP (2006), AERGA (2006), and APATH (2007).

Discussion of the Analysis

It is a sound decision not to do the numerical analysis at this time, since the results would be quite speculative due to many uncertainties. First, the implementation and its schedule of new NAS architecture are unpredictable even though it should serve as a plan, evidenced by its ever-evolving scope and schedule. The congressional budgetary process and the need to satisfy all the stakeholders of NAS are the two major uncertainty sources of the new architecture. On the operational level, we do not have a clear estimate of the cost of the new NAS and its improvement to airlines.

However, the uncertainties do not preclude us from discussing how we might undertake the analysis differently under the new NAS assumption. One of the main objectives of new NAS architecture is to maintain and enhance the existing ATC service, managed in an evolutionary manner. This means that the airlines will conduct the same kind of flight operations, albeit improved, in the future;

although the tools and the ways to conduct the operations may be different. This further means that the methodology and the business strategies we proposed in Chapter 3 also must apply when the new NAS architecture is assumed; the difference lies in the degree of change but not the framework.

In our previous studies, we modeled the impact of TAP and AATT technologies on NAS [14, 15]. Our approach to evaluate the operational impact of new NAS will be the same: first take the LMI Airport Capacity Model and the Functional Analysis Model (FAM) to get the new airport and air traffic service sector capacities, which will be used as parameter input to compute flight delays in the Operations Model.

The parameters used in ACIM also will have to be modified. The airlines will incur two additional costs: to install the necessary equipment themselves and to pay higher user fees resulting from the upgraded ATC system upgrading. The airlines will achieve some cost savings due to more efficient flight profiles, which can be computed by the ASAC Mission Generator and Network Cost Generator. The savings from the decreased flight delays and its impact on air travel demand are computed by the closed loop of the Operation model and ACIM. The possibility of business growth offered by the new NAS architecture actually is very important to the airlines, and it is not addressed explicitly in the closed loop of the Operation model and ACIM but could be captured via modification of the TAF.

Chapter 5
Summary and Future Work

RESULTS

In this task we identified and analyzed potential operational strategies that air carriers may adopt to meet unconstrained traffic growth in the face of current limited airport capacities. We developed a unique and powerful capability to link technical models of National Airspace System (NAS) capacity with airline economic models. The models are fast enough to allow efficient investigation of multiple strategies and accurate enough to identify with confidence the relative benefits of those strategies. The models also provide the capability to analyze airline strategies in combination with the NASA Advanced Air Transportation Technology (AATT) research projects.

Based on the results of the current analysis, we predict a substantial loss of potential traffic growth due to NAS congestion if the air carriers continue their current business strategies. The effectiveness of alternative business strategies varies depending on the airport. Several alternatives, including fare adjustments, new hubs, direct origin-to-destination flights, schedule smoothing, nighttime operations, and larger aircraft reduce predicted congestion; however, even with combinations of strategies, congestion still reduces the level of traffic growth compared to unconstrained predictions. This finding reinforces the importance of NASA and FAA sponsored projects to increase airport capacities.

We have confidence in our conclusions because the component models have been validated and our methodology of using an economic model to reflect the air carriers' decisions is generally sound. There are limitations to the current analysis that should be addressed in future work.

ANALYSIS LIMITATIONS

Lack of detailed schedule predictions prevents us from using more sophisticated models. Specifically, the use of the log-linear model for estimating schedule response to delays, and the use of a semi-empirical delay multiplier are limitations that could be addressed through the use of detailed simulation models. With simulation models we could investigate whether the relationship of schedule to delays becomes non-linear at some critical value with subsequent loss of schedule integrity. We might also be able to determine the true ripple effect of delays.

In the current study we do not address the technical or business feasibility of implementing the airline alternatives. All alternatives were considered equally likely.

Finally, in the current study we did not estimate the costs of the alternative strategies.

FUTURE WORK

The current work is an important first step in understanding and forecasting the air carrier's future operating strategies and the potential benefits of the AATT program. The current tools can be used directly to investigate the benefits and costs of AATT technologies. Additions to the current tools can provide detailed insight into AATT impact at selected airports, and might even have tactical use. Based on the results of the current effort we recommend the following tasks for future work.

AATT Cost Benefit Analysis

AATT cost benefit analysis can be conducted with the existing models. Benefits can be estimated by using input values for individual and/or combined AATT tools along with individual and/or combined airline strategies. No major model modifications are required for such an analysis.

Costs can be estimated separately for each AATT tool set and airline strategy. Cost analysis of the scenarios should include not just the costs to the air carrier, but also other expenses such as the cost to the airport authorities, costs to the federal government, and costs to the local communities around the airports.

AATT and Airline Strategy Technical Feasibility Analysis

Technical feasibility for selected airports can be conducted by collecting data on technical requirements versus constraints. Feasibility analyses would consider all aspects of a flight schedule, including, but not limited to, ATC procedures, airport configurations and limitations, gate capacity, airline maintenance facilities, airport ground access, government regulation, and air carrier marketing limitations.

Combined Simulation-Analytic Modeling

Linking detailed simulations (using models such as TAAM) for selected airports to the analytic LMINET models can provide both improved insight into AATT development issues and a potential tactical ATC tool. Such simulations can be initially used to investigate assumptions in the basic models, such as non-linear schedule responses to delays and delay ripple effects. Ultimately, simulation-coupled models can evaluate the impacts of airline and ATC tactical responses to congestion. The first steps in development of the simulation-coupled models are identification of the airports to be simulated, construction of detailed OAG-like flight schedules for those airports, and development of the integration software need to couple the analytic and simulation models.

Detailed Future Flight Schedules

The construction of OAG-like future flight schedules is recommended as a task in its own right. Such schedules are needed as inputs for all simulation models that analyze air traffic operations. By generating such schedules for different airline business strategies, the AATT program can better evaluate it products in a more realistic future environment.

Appendix A
Airport Capacity Enhancement

While the airport capacity models we used in this study are validated for their current operations, some of the models needed updating to incorporate the most recent projections of future runway configurations. This appendix describes the methodology used to update the capacity models , along with the list of those airports whose models required updating Updated models for all the airports, except ATL, can be built from our current standard suite of runway models. The new capacity model developed for ATL is described in the last section of this appendix.

METHODOLOGY

In updating LMINET, we considered the proposed airport capacity enhancements of the 1997 and 1998 FAA Aviation Capacity Enhancement (ACE) Plans. ACE Plans provide a comprehensive review of the FAA's programs that are intended to improve the capacity of the nation's Air Transportation System. The 1997 and 1998 Aviation Capacity Enhancement Plan Online Databases (ACE Databases) are electronic references based on the 1997 and 1998 ACE Plans, which are produced by the Federal Aviation Administration, Office of System Capacity. For the top 100 airports covered in the 1997 and 1998 ACE Plans, the databases contain relevant information in the areas of airport enplanements, operations, and delay statistics; planned or proposed runway construction; airport diagrams; and some of the physical descriptions of the airport's runways. [25]

We used ACE databases to identify proposed airport capacity enhancements for the 64 LMINET airports. In particular, we gathered information on the most recent proposed airport improvement plans and enhancements, as well as those enhancements that are already implemented at the 64 airports currently included in LMINET. In view of frequently changing airport construction plans, and since the objective is to include only those enhancements that are nearly certain to be realized, we include the enhancements in the updated model only when

- construction has begun already,
- construction is near commencement, or
- an environmental impact study has been completed.

The enhancements identified were used to revise the existing version of LMINET. As a result of these changes, the model is more accurate in reflecting how the NAS will operate over the next several years.

FINDINGS

Twenty-one LMINET airport capacity models required updating Updates include new runways, major extensions of existing runways, and the closing of existing runways. Also, our modeling approach to the airport capacity models in LMINET was changed to accommodate commuter-only runways at ATL, BOS, MKE, and PHL. Table A-1 illustrates the current and revised LMINET capacity functions for each of the 21 airports that meet the enhancement criteria.

Table A-1. Updated LMINET Airport Capacity Models

Airport Code	Original LMINET capacity models	Updated capacity models	Updated models in current LMINET
ATL	stdcap4h	atlcap	X
BSM (AUS)	stdcap1xb	stdcap21	X
BWI	stdcap1ya	stdcap21	X
CLE	stdcap21b	stdcap21	X
CLT	cltcap	stdcap3	X
CVG	stdcap2	stdcap3	X
DTW	stdcap3h	dtwcap	
FLL	stdcap2b	stdcap2	X
GSO	stdcap1xa	stdcap2	X
MCO	stdcap2	mcocap	
MEM	stdcap21	memcap	
MIA	stdcap2bh	miacap	
MKE	stdcap1xa	boscap	X
MSP	stdcap21ah	mspcap	
MSY	stdcap1x	stdcap2	X
PHL	stdcap21a	phlcap	
PHX	stdcap21b	stdcap3	X
SEA	stdcap21	stdcap3h	X
SJC	stdcap1xb	sjccap	
STL	indcap	stdcap4	X
SYR	stdcap1xa	stdcap21	

Note: The extensions a, b, and h denote no CAT III, no CAT II or III, and international/heavy airports, respectively.

For the analyses documented in this report, LMINET includes updated models for the following airports: ATL, BSM, BWI, CLE, CLT, CVG, FLL, GSO, MKE, MSY, PHX, SEA, STL, and SYR. The rest of the airports—DTW, MCO, MEM, MIA, MSP, PHL, and SJC— need to be updated in future work.

REVISED ATL CAPACITY MODEL

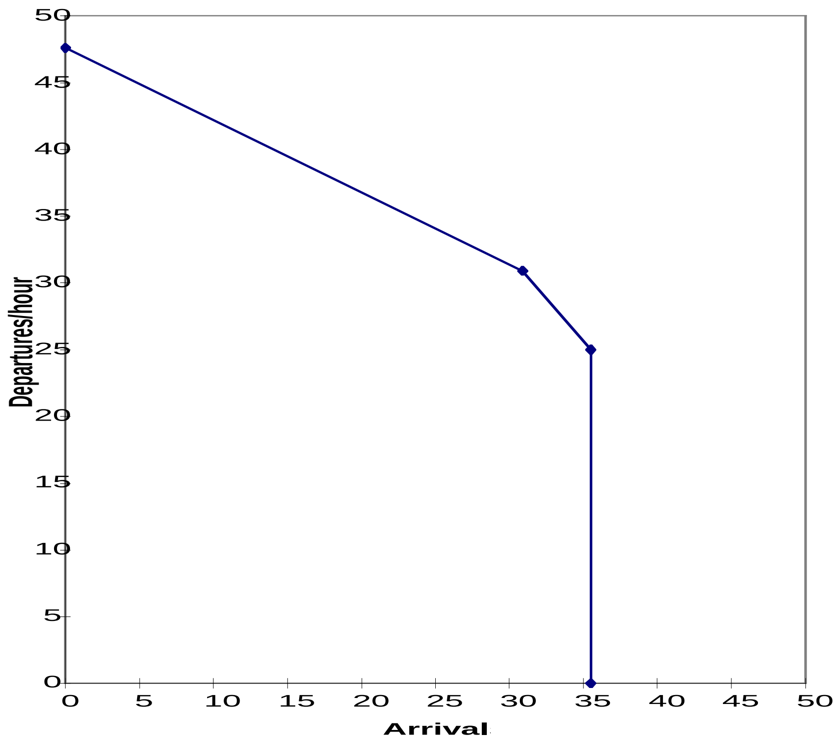
The likelihood that ATL will implement a fifth parallel runway for commuter arrivals calls for a new capacity model that cannot be built from the existing model suite.

Present Model

Presently, ATL has two sets of two parallel runways. The sets are sufficiently widely spaced for independent operations, but the two members of each set are not. The present ATL model for LMINET is an adjustment to a specific representation of the airport, which accounts for ATL's observed performance. In this model, in VMC the airport is modeled as having the same capacity as three independent runways on which the arrival/departure mix is adjusted to meet demand. This reflects, crudely, the fact that ATL can run staggered arrivals and departures on both runways of each closely spaced pair in VMC. In IMC, the airport is treated as equivalent to two independent runways on which the arrival-departure mix is adjusted to meet demand.

In this model, the capacity of a runway is taken to be a Pareto frontier in the arrival-rate, departure-rate plane. We characterize such frontiers by the four points (0, D), (E, E), (A, F) and (A, 0). Thus, D is the departure rate when the runway is devoted to departures; E, the departure and arrival rate when the runway operates with equal departure and arrival rates; A, the arrival rate when the runway is devoted to arrivals; and F, the largest rate at which departures can be accommodated while the runway accepts arrivals at the maximal rate A. Figure A-1 shows an example.

Figure A-1. Pareto Frontier (Capacity) at ATL for VMC 1



In the present ATL model, the values of D, E, A, and F are the standard ones for international airports in LMINET. Table A-2 shows these values.

Table A-2. Pareto Frontier Parameters

Condition	D	E	A	F
VMC 1	47.6	30.9	35.5	25
VMC 2	45.5	29.2	31.0	26
IMC 1	42.3	23.1	29.0	11
IMC 2	42.3	21.9	29.0	8
IMC 3	42.3	21.9	29.0	8

Effects of an Independent Commuter Arrival Runway

In addition to the obvious effect of adding the arrival capacity of one runway, adding an independent runway for commuter arrivals will increase the capacity of ATL's other four runways by removing smaller aircraft from their arrival traffic streams. Small aircraft arriving behind heavy aircraft, or Boeing 757s, require greater spacing than do large aircraft following such leaders.

Small aircraft make up 21 percent of ATL's current traffic. Segregating this traffic has a significant effect. As an example, Table A-3 shows the variation of Pareto parameters at ATL for the present model, for the specific mix of aircraft types presently found at ATL, for ATL with only small aircraft using the runway, and for ATL with no small aircraft in the mix. The table is for meteorological condition IMC 1.

Table A-3. Pareto Parameters at ATL for IMC 1

Aircraft mix	D	E	A	F
Present model	42.3	23.1	29.0	11
Present ATL	44.8	22.7	29.3	10
ATL, small only	37.3	24.2	30.5	13
ATL, no small	46.6	22.5	29.8	8

Revised Model

In view of the effects discussed in the preceding subsection, we revised the LMINET capacity model for ATL to reflect adding an independent runway for commuter arrivals. We determined the arrival and departure capacities of the present runway system when presented with 79 percent of the actual arrivals (i.e., deleting the 21 percent of arrivals that will use the new runway) and when the mix of arrivals contains no small aircraft. Since the commuter runway is to be used for arrivals only, we maintained the departure mix at the standard values for ATL. This generated the Pareto parameters of Table A-4. We then added to the arrival capacity the arrival capacity of a runway devoted solely to small aircraft. Table A-5 shows these capacities.

Table A-4. Pareto Parameters at ATL with No Small Aircraft in Arrival Mix

Weather Condition	D	E	A	F
VMC 1	52.0	25.6	35.9	14
VMC 2	48.8	25.4	32.2	19
IMC 1	44.8	25.4	29.8	21
IMC 2	44.8	24.0	29.8	18
IMC 3	44.8	24.0	29.8	18

This assignment scheme would not be reasonable if it caused significant imbalance of demands on ATL's several runways. However, with 21 percent as small traffic and with present ATL demand patterns, such imbalances do not seem to occur.

Table A-5. Arrival Capacities of ATL Runway with Only Small Aircraft in Mix

Weather Condition	Capacity
VMC 1	35.9
VMC 2	32.2
IMC 1	29.8
IMC 2	29.8
IMC 3	29.8

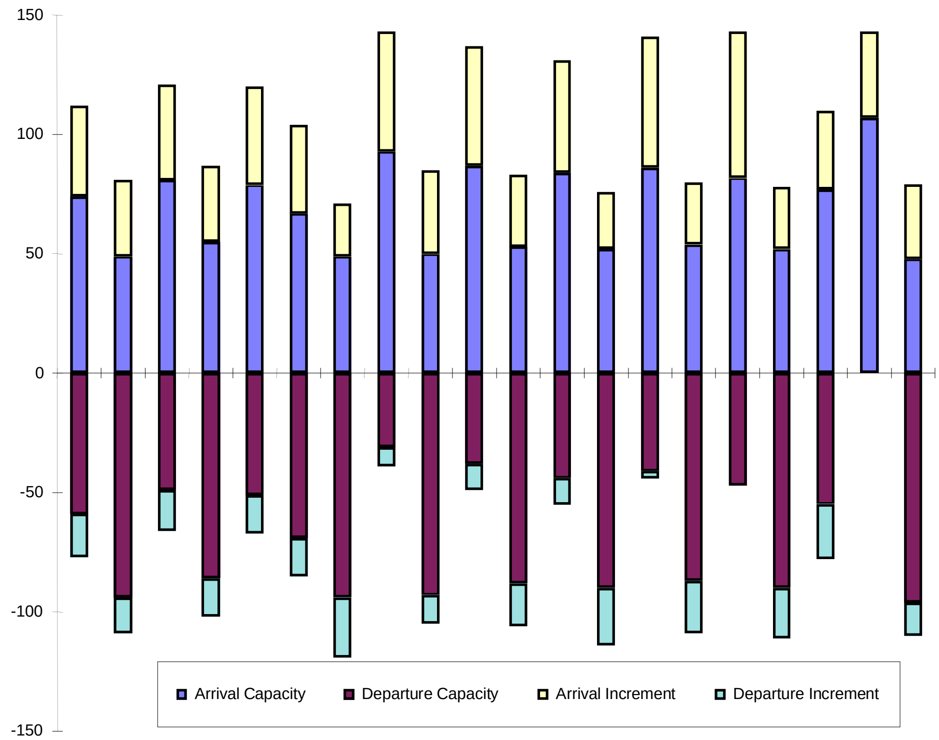
Illustration of Capacity Changes

Table A-6 and Figure A-2 show the effects on capacity at ATL as demand varies according to 1996 patterns throughout a day. Epoch 0 is 6:00 a.m. Eastern Standard Time.

Table A-6. Hourly Arrival and Departure Capacities for Original and Revised Models, by Epoch

	Original		Revised	
Epoch	Arrival	Departure	Arrival	Departure
0	21	133	53	137
1	74	59	112	77
2	49	94	81	109
3	81	49	121	66
4	55	86	87	102
5	79	51	120	67
6	67	69	104	85
7	49	94	71	119
8	93	31	143	39
9	50	93	85	105
10	87	38	137	49
11	53	88	83	106
12	84	44	131	55
13	52	90	76	114
14	86	41	141	44
15	54	87	80	109
16	82	47	143	40
17	52	90	78	111
18	77	55	110	78
19	107	0	143	0
20	48	96	79	110

Figure A-2. Hourly Arrival and Departure Capacities for Original and Revised Models



The modest increments in departure capacity are mostly due to the improved arrival mix. Nothing to do with air traffic management is simple, however, and the details of the capacity changes are due to the detailed working of the capacity model as it selects the point on the combined Pareto frontier that best meets arrival and departure demands. This work of the capacity model is the reason why the change in arrival capacity is not always just the capacity of the new runway: when departure demand exceeds arrival demand, the system may trade arrivals for departures on the joint-use runways.

Appendix B
Model Equations for the M/Ek/1 → ../M/1 and the M/M/1 → ../Ek/1 Tandem Queuing Networks

This appendix explains the development of model equations for two tandem queuing networks, which is the model for both arrival and department queues in our airport model. In the case of the arrival queuing model, a M/Ek/1 queue precedes a queue with exponentially distributed service times. In the case of the departure queuing model, a M/M/1 queue precedes a queue whose service times have the Ek distribution. Table B-1 defines the variables and symbols used in this appendix.

Table B-1. Variables And Symbols Used

Parameter	Units	Description
M	n/a	Poisson distribution
E_K	n/a	Erlang distribution with k internal states
../M/1	n/a	network queue with arrivals controlled by previous queue output, a Poisson service distribution, and 1 server
../E_K/1	n/a	network queue with arrivals controlled by previous queue output, an Erlang service distribution, and 1 server
p (i,j,t)	probability	For the M/E_k/1 → ../M/1 tandem system, p(i, j, t) is the probability that i phases are in the M/E_K/1 queue, and j aircraft are in the ../M/1 queue at time t. For the M/M/1 → ../E_k/1 tandem system, p(i, j, t) is the probability that i aircraft are in the M/M/1 queue and j phases are in the ../E_k/1 queue at time t.
λ	aircraft/time	mean arrival rate
μ	phases/time	mean service rate in M/E_K/1 queue
μ_2	aircraft/time	mean service rate in ../M/1 queue
k	n. d.	order of the E_k distribution
t	time	time
A/S/N	n/a	identifies a queue (system) in which interarrival times have distribution A, service times have distribution S, and in which there are N servers.
GI	n/a	General Independent distribution
q_r	aircraft	model runway queue length
q_t	aircraft	model taxi queue length
v_t	$(\text{aircraft})^2$	model taxi queue variance
o_r	aircraft/time	runway queue departure rate
o_t	aircraft/time	taxi queue departure rate
ρ	n. d.	λ/μ, ratio of arrival rate to runway service rate
ρ_t	n. d.	λ/μ_t, ratio of arrival rate to taxi service rate
p_0	probability	probability of zero aircraft in the queue system

Table B-1. Variables And Symbols Used (Continued)

W_{qr}	time	runway waiting time
L_{qr}	aircraft	number of aircraft in runway queue
p_n	probability	number of phases in the $M/E_K/1$ queue
s(t)	1/time	probability distribution of service times for $M/E_K/1$ queue
d(t)	1/time	probability distribution of interdeparture times for $M/E_k/1$ queue
$\hat{p}_n$	probability	probability that n aircraft are in the ../M/1 queue
μ_t	aircraft/time	mean service rate of ../M/1 queue
L_{qt}	aircraft	Mean number of aircraft in ../M/1 queue

Note: a dot above a function indicates the time rate-of-change of the function

$M/E_K/1 \rightarrow$.. /M/1

As derived in our previous work [15], exact evolution equations for this network are

$$\dot{p}(0,0,t) = -\lambda p(0,0,t) + \mu_2 p(0,1,t) \qquad \text{[Eq. B-1]}$$

$$\begin{aligned}\dot{p}(0,n_2,t) = &-(\lambda+\mu_2)p(0,n_2,t)\\ &+k\mu p(1,n_2-1,t)\\ &+\mu_2 p(0,n_2+1,t),\ n_2>0\end{aligned} \qquad \text{[Eq. B-2]}$$

$$\begin{aligned}\dot{p}(n_1,0,t) = &-(\lambda+k\mu)p(n_1,0,t)\\ &+k\mu p(n_1+1,0,t)\\ &+\mu_2 p(n_1,1,t),\ 0<n_1<k\end{aligned} \qquad \text{[Eq. B-3]}$$

$$\begin{aligned}\dot{p}(n_1,0,t) = &-(\lambda+k\mu)p(n_1,0,t)\\ &+k\mu p(n_1+1,0,t)\\ &+\mu_2 p(n_1,1,t)\\ &+\lambda p(n_1-k,0,t),\quad n_1\ ?\ k, n_1\ ?\ mk, m=1,2,\ldots,\end{aligned} \qquad \text{[Eq. B-4]}$$

$$\begin{aligned}\dot{p}(mk,0,t) = &-(\lambda+k\mu)p(mk,0,t)\\ &+\mu_2 p(mk,1,t)\\ &+\lambda p[(m-1)k,0,t)],\ m=1,2,\ldots,\end{aligned} \qquad \text{[Eq. B-5]}$$

$$\begin{aligned}\dot{p}(n_1,n_2,t) = &-(\lambda+k\mu+\mu_2)p(n_1,n_2,t)\\ &+k\mu p(n_1+1,n2,t)\\ &+\mu_2 p(n_1,n_2+1,t),\quad 0<n_1<k; n_2>0\end{aligned} \qquad \text{[Eq. B-6]}$$

$$\begin{aligned}\dot{p}(n_1,n_2,t) = &-(\lambda + k\mu + \mu_2)\,p(n_1,n_2,t)\\ &+ k\mu p(n_1+1,n2,t)\\ &+ \mu_2\,p(n_1,n_2+1,t)\\ &+ \lambda p(n_1-k,n_2,t), \qquad n_1 \ ?\ k; n_1 \ ?\ mk; n_2 > 0\end{aligned} \qquad \text{[Eq. B-7]}$$

$$\begin{aligned}\dot{p}(mk,n_2,t) = &-(\lambda + k\mu + \mu_2)\,p(mk,n_2,t)\\ &+ k\mu p(mk+1,n2-1,t)\\ &+ \mu_2\,p(mk,n_2+1,t)\\ &+ \lambda p[(m-1)k,n_2,t)], \qquad n_2 > 0; m \ ?\ 1\end{aligned} \qquad \text{[Eq. B-8]}$$

In Equations B-1 through B-8, $p(i, j, t)$ is the probability that i phases are in the M/Ek/1 queue, and j clients are in the ../M/1 queue, at time t. Lambda is the mean arrival rate, μ is the mean service rate in the M/Ek/1 queue, and μ_2 is the mean service rate in the ../M/1 queue.

It is possible to obtain useful results from numerical solutions of this system, as reported in Reference [35, pp.240]. However, there are three reasons why this work is somewhat tedious. First, many dependent variables $p(n1, n2)$ must be carried for cases in which even moderate queues are present. Numerical experiments indicate that one must allow the first index to range from zero through roughly 5,000 times the mean number of clients in the first system, while allowing the second index to range from zero to roughly 10 times the number of clients in the second queue. This leads to carrying tens of thousands of dependent variables. Fortunately, the drastic sparseness of Equations B-1 through B-8 allows this to be done with acceptable computing times for many cases of interest in air traffic modeling.

The second difficulty is that many time scales must be considered to treat the system of differential equations adequately, some of which are relatively short. Typically, step sizes no larger than $1/(k\mu)$ must be used. Since some relevant time scales also are relatively long, on the order of hundreds of service times, steady-state results usually are not directly useful for airport modeling.

Finally, tracking an airport over an entire day, or even over a busy period of an hour or so, requires continuing numerical integrations over thousands of steps.

These unpleasant facts stimulate a search for model equations that can be used for exploratory calculations. After discussing the exact steady-state solution of the tandem network in the next section, we develop a set of these in subsequent sections.

The Model Equations

Our objective here is to develop rapidly solvable, empirically justified model equations, *not* to develop rational approximations to the solutions of Equations B-1 through B-8. We initially planned to use the resulting model equations for preliminary calculations only, however, the results, as will be shown later, turned out to be sufficiently accurate to justify their use for the final calculations. We begin with a subset of the equations used in LMINET [15]. This subset represents traffic arriving before a queue for runway service and exiting that queue into a queue for taxi runway service. These equations are

$$\dot{q}_r = \lambda - \mu + \mu \frac{k+1}{k+1+2kq_r} \qquad \text{[Eq. B-9]}$$

$$o_r = \lambda - \dot{q}_r = \mu\left(1 - \frac{k+1}{k+1+2kq_r}\right) \qquad \text{[Eq. B-10]}$$

$$\dot{q}_t = o_r - \mu_2\left(1 - p_0(q_t, v_t)\right) \qquad \text{[Eq. B-11]}$$

$$\dot{v}_t = o_r + \mu_2\left[1 - (2q_t + 1)\, p_0(q_t, v_t)\right] \qquad \text{[Eq. B-12]}$$

$$p_0(q_t, v_t) \ldots \left(\frac{q_t}{v_t}\right)^{\frac{q_t^2}{v_t - q_t}} \qquad \text{[Eq. B-13]}$$

Equation B-9 comes from a first-moment closure approximation to the equations for the probabilities of the number of phases in a M/Ek/1 queue. Equations B-11 through B-13 are adapted from the second-moment closure approximation of Rothkopf and Oren for the probabilities of the number of clients in a M/M/1 queue [30].

Waiting Time and Queue Length in the Runway Queue

In this subsection we use known steady-state results to adapt the LMINET model equations into new model equations that give better approximations to the exact solutions of the M/Ek/1 $\rightarrow$ ../M/1 tandem queue network.

In steady state, Equation B-9 leads to

$$q_r = \frac{1}{2}\left(\frac{k+1}{k}\right)\left(\frac{\rho}{1-\rho}\right) \qquad \text{[Eq. B-14]}$$

If we were to take this limiting value of q_r divided by μ as a value for runway waiting time W_{qr}, we would have

$$W_{qr} = \frac{1}{2}\left(\frac{1}{\mu}\frac{k+1}{k}\right)\left(\frac{\rho}{1-\rho}\right) \qquad \text{[Eq. B-15]}$$

which is the correct value for steady-state waiting time in the M/Ek/1 queue [34, pp. 173]. Accordingly, we will use

$$W_{qr} = \frac{q_r}{\mu} \qquad \text{[Eq. B-16]}$$

as our model's approximation for waiting time W_{qr}.

In steady state, the product of λ with W_{qr} gives the number in the runway queue, L_{qr}. Accordingly, when steady state conditions are likely to prevail toward the end of an epoch, we take

$$L_{qr} = \lambda \frac{q_r}{\mu} \qquad \text{[Eq. B-17]}$$

Numerical experiments indicate that Equation B-16 should be used to evaluate L_{qr} when the utilization ratio $\rho = \lambda/\mu$ is smaller than about 0.85.

For larger values of the utilization ratio, we find a different approximation is better. This "heavy traffic" approximation follows from estimating the number of aircraft waiting as the expected number of phases greater than k in the M/Ek/1 queue, divided by k. The rationale of this estimate is that each client brings k phases to the queue, and 1 through k phases in the system represent a client in service.

Thus, in this approximation we estimate L_{qr} as

$$L_{qr} \approx \frac{1}{k}\sum_{k+1}^{\infty}(n-k)p_n - \frac{1}{k}\sum_{1}^{k} np_n - \left(1 - \sum_{0}^{k} p_n\right) \qquad \text{[Eq. B-18]}$$

where p_n denotes the number of phases in the M/Ek/1 queue.

Now, in steady state, the evolution equations for the p_n reduce to

$$p_n = \frac{\lambda(\lambda + k\mu)^{n-1}}{(k\mu)^n} \cdot p_0, 1 \le n \le k \qquad \text{[Eq. B-19]}$$

Using this result, and the approximation

$$p_0 \approx \frac{k+1}{k+1+2kq_r} \qquad \text{[Eq. B-20])}$$

that underlies Equation B-9, leads after some manipulation to

$$L_{qr} \approx q_r - 1 + \frac{p_0}{\rho}\left[(1+\rho/k)^k - 1\right] \qquad \text{[Eq. B-21]}$$

We use the approximation in Equation B-20 for L_{qr} when ρ is not less than 0.85; otherwise, we use the approximation in Equation B-16

COMPARISON WITH NUMERICAL RESULTS FOR THE FULL EQUATIONS

We take as examples of "typical" and "heavy load" cases the following demand and capacity data as shown in Tables B-2 and B-3.

Table B-2. Arrival Demand at DTW

Taxi-in capacity 87.95 per hour		
Epoch	Per-hour demand	Per-hour capacity
0	7.2	66.4
1	12.5	31.0
2	30.3	62.0
3	27.3	50.3
4	26.4	35.5
5	50.6	62.0
6	51.7	67.0
7	31.2	35.5
8	65.3	71.0
9	41.4	57.4
10	65.7	71.0
11	50.1	71.0
12	50.4	71.0
13	50.7	71.0
14	43.9	55.0
15	65.5	71.0
16	6.8	66.4
17	13.8	66.4
18	5.1	66.4
19	1.2	66.4
20	1.2	66.4

Table B-3. Arrival Demand at ATL

Taxi-in capacity 96.2 per hour		
Epoch	Per Hour Demand	Per Hour Capacity
0	2.2	89.9
1	6.3	94.7
2	2.6	91.7
3	2.9	92.8
4	6.8	95
5	46.6	106.5
6	12.2	25.8
7	101.5	106.5
8	105.4	64.2
9	107.8	106.5
10	115.8	78.3
11	87.7	98.5
12	143.8	97.6
13	52.8	40.5
14	159.7	106.5
15	83	57.4
16	131.6	106.5
17	134	74.2
18	110.5	106.5
19	100.4	61.8
20	105	106.5
21	100.1	71.4
22	99.3	106.5
23	22.7	36.2

Results for L_{qr} from “exact” numerical solutions of Equations B-1 through B-8 are compared with those of the model equations in Figures B-1 and B-2.

Figure B–1. Model Results and "Exact" Results for DTW Arrivals

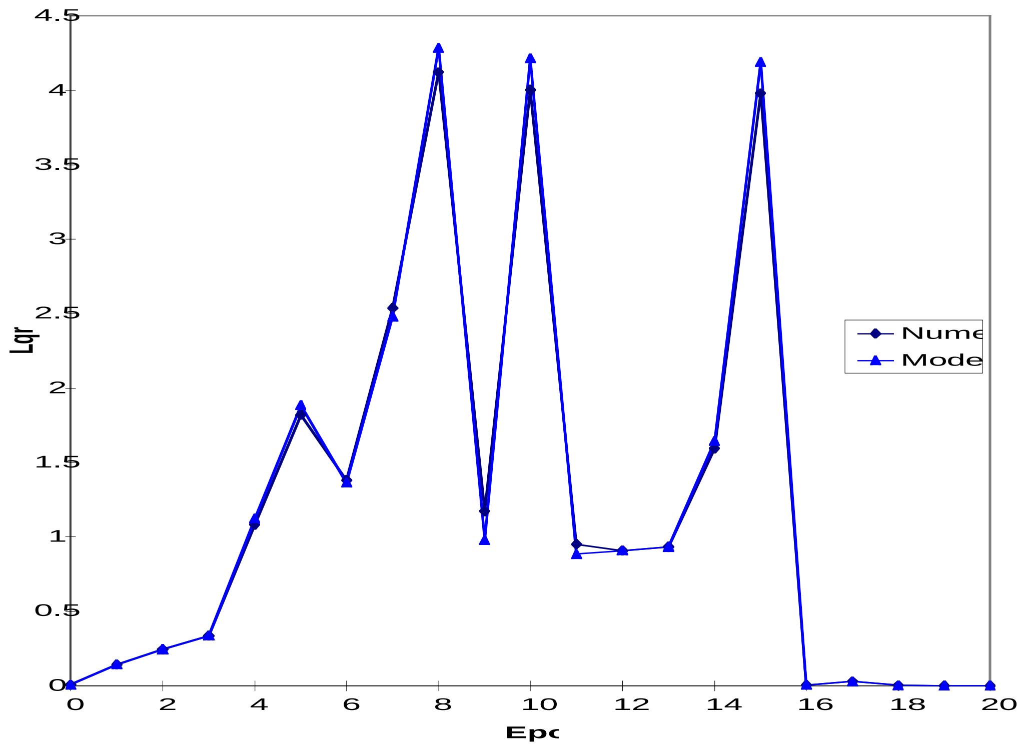
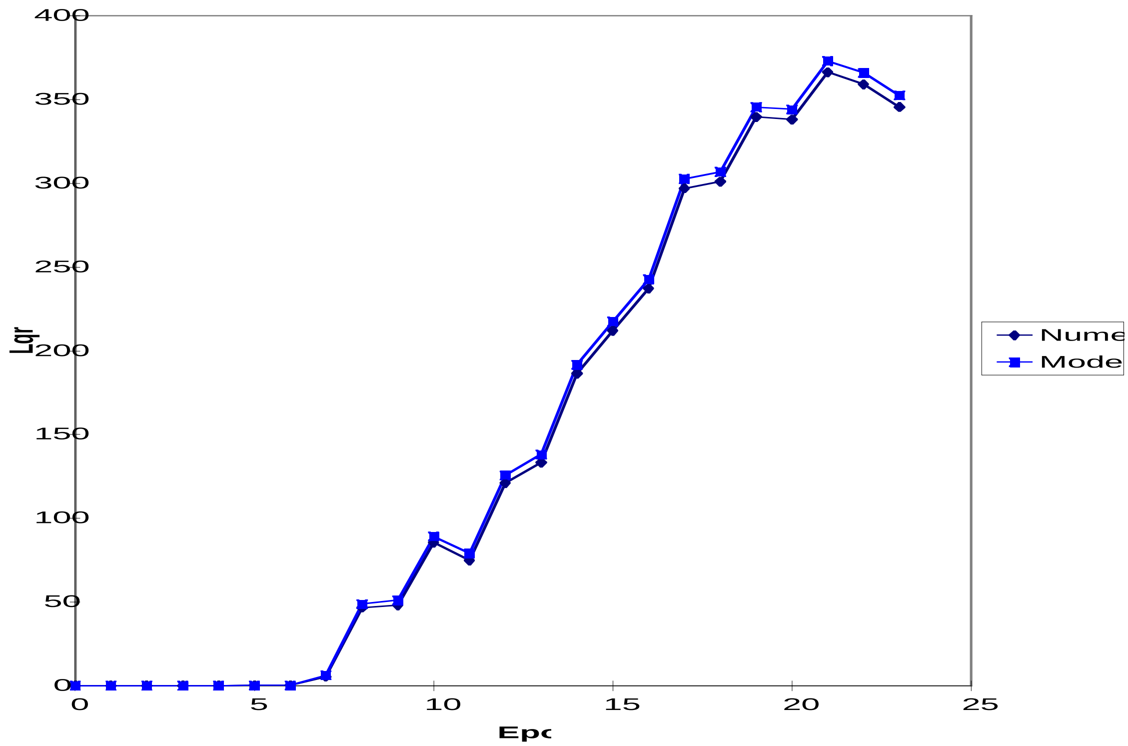


Figure B–2. Model Results and "Exact" Results for ATL Arrivals



Waiting Time and Queue Length in the Taxi Queue

In this section, we develop adaptations of the LMINET equations that give useful approximations to the number of aircraft in the taxi-in queue. Again, considering steady-state results suggests the adaptations.

The exact steady-state solution for the M/Ek/1 queue is known [35, pp.240], including the distribution of inter-departure times [35, pp.254]. Since exact steady-state results are also available for the GI/M/1 queue [35, pp.274], it is tempting to think of combining these results to give the exact steady state of the tandem network. That does not work, however, because the inter-departure of the M/Ek/1 queue is not independent,
unless $k = 1$.

Nevertheless, the solution of the GI/M/1 queue for independent inter-arrival times with the same distribution as the inter-departure times of the M/Ek/1 queue will prove useful to us, and we now develop that result.

The exact probability distribution function of inter-departure times from the M/Ek/1 queue, $d(t)$, is determined by

$$d(t) = \rho s(t) + (1-\rho)\int_0^t s(t-\tau)\lambda e^{-\lambda\tau}d\tau \qquad \text{[Eq. B-22]}$$

where $s(t)$ is the probability distribution function of service times, ρ is the utilization ratio, and λ is the mean arrival rate [35]. Noting that the integral of Equation B-22 is a convolution, we see that $D(s)$, the Laplace transform of $d(t)$, is given by

$$D(s) = \left[\rho + (1-\rho)\frac{\lambda}{s+\lambda}\right]S(s) \qquad \text{[Eq. B-23]}$$

where $S(s)$ is the Laplace transform of $s(t)$.

When the service process is Ek, Equation B-23 becomes

$$D(s) = \left[\rho + (1-\rho)\frac{\lambda}{s+\lambda}\right]\left[\frac{k}{s+k}\right]^{k} \qquad \text{[Eq. B-24]}$$

The exact steady-state distribution for the number of clients in a GI/M/1 queue is known [36, pp.251]. If p_n is the probability that n clients are in the system in steady state, then for n not less than one,

$$p_n = \rho(1-z_0)z_0^{n-1} \qquad \text{[Eq. B-25]}$$

where z_0 is the unique real root in (0,1) of the equation

$$z = \lambda(\mu(1-z)) \qquad \text{[Eq. B-26]}$$

Thus, in the steady state, the probability $\hat{p}_n$ that n clients are in the ../M/1 queue will be given by

$$\hat{p}_n = \rho_t(1-r_0)r_0^{n-1} \qquad \text{[Eq. B-27]}$$

where r_0 is the unique root in (0, 1) of

$$r = \left[\rho + (1-\rho)\frac{\lambda}{\mu_t(1-r)+\lambda}\right]\left[\frac{k\mu}{\mu_t(1-r)+k\mu}\right]^{k} \qquad \text{[Eq. B-28]}$$

In Equation B-28, $\rho = \lambda/\mu$, and μ_t is the mean service rate in the ../M/1 queue. From Equation B-27, it follows that L_{qt}, the mean number of clients waiting in the ../M/1 queue, is given by

$$L_{qt} = \frac{\rho_t r_0}{1-r_0} \qquad \text{[Eq. B-29]}$$

and the mean number L_t of clients in the ../M/1 queue, including any clients in service, is

$$L_t = \frac{\rho_t}{1 - r_0} \qquad \text{[Eq. B-30]}$$

Now we will use these steady-state results, particularly those of Equations B-29 and B-30, to develop model equations. In the steady state, Equations B-9 through Equation B-13 lead to

$$q_t = \frac{\rho_t}{1 - \rho_t} \qquad \text{[Eq. B-31]}$$

where ρ_t is defined as λ/μ_t. This is, of course, the steady-state solution for the mean number in a M/M/1 queue, with input rate λ and service rate μ_t.

In general, the number waiting in the queue, L_q, is related to the number L in the system by

$$L_q = L - (1 - p_0) \qquad \text{[Eq. B-32]}$$

In steady state, q_t - (1 - p_0) has the limiting behavior

$$q_t - (1 - p_0) \blacklozenge \frac{\rho_t^2}{1 - \rho_t} \qquad \text{[Eq. B-33]}$$

which is the steady-state number enqueued in a M/M/1 system.

Although the taxi queue in steady state is not *exactly* the queue for which L_{qt} is given by Equation B-28, we will find that correcting the LMINET result q_t - (1 - p_0) to yield the steady-state result in Equation B-29 gives a useful result. Accordingly, when both ρ and ρ_t are less than one, we approximate L_{qt} as

$$L_{qt} \cup \left[q_t - (1 - p_0)\right]\frac{1 - \rho_t}{\rho_t} \leftrightarrow \frac{r_0}{1 - r_0} \qquad \text{[Eq. B-34]}$$

When ρ is larger than one, but the ratio μ/μ_t is less than one, we may expect the taxi queue to behave somewhat like an Ek/M/1 queue, with mean input rate μ. Applying the GI/M/1 results of Equations B-25 and B-26 to this case, we find that, in steady state,

$$L_{qt} \cup \frac{s_0}{1 - s_0}\frac{\mu}{\mu_t} \qquad \text{[Eq. B-35]}$$

where s_0 is the root in (0,1) of

$$s = \frac{k\mu}{k\mu + \mu_t(1-s)}^{k} \qquad \text{[Eq. B-36]}$$

When $\lambda > \mu$ and $\mu < \mu_t$, even though the system has no steady state because the M/Ek/1 queue is unstable, q_t-(1-p_0) has the limiting behavior

$$q_t - (1-p_0) \blacklozenge \frac{(\mu/\mu_t)^2}{1-(\mu/\mu_t)} \qquad \text{[Eq. B-37]}$$

Accordingly, when $\lambda > \mu$ and $\mu < \mu_t$, we approximate L_{qt} by

$$L_{qt} \cup \left[q_t - (1-p_0)\right]\frac{1-\mu/\mu_t}{\mu/\mu_t} \leftrightarrow \frac{s_0}{1-s_0} \qquad \text{[Eq. B-38]}$$

For cases where neither the runway nor the taxiway queue has a steady state, we find by numerical experiment that the approximation

$$L_{qt} \cup 0.85\left[q_t - (1-p_0)\right] \qquad \text{[Eq. B-39]}$$

is reasonably good, and we use it.

Comparison with Numerical Results for the Full Equations

Figures B-3 and B-4 show the agreement between numerical solutions of the full Equations B-1 through B-8 with solutions of the model equations described above for the number of aircraft enqueued in the taxi-in queue. The taxi capacities, and the hour-by-hour demands and runway capacities, are given in Table B-2 for DTW, and in Table B-3 for ATL.

Figure B–3. Taxi-in Queue at DTW

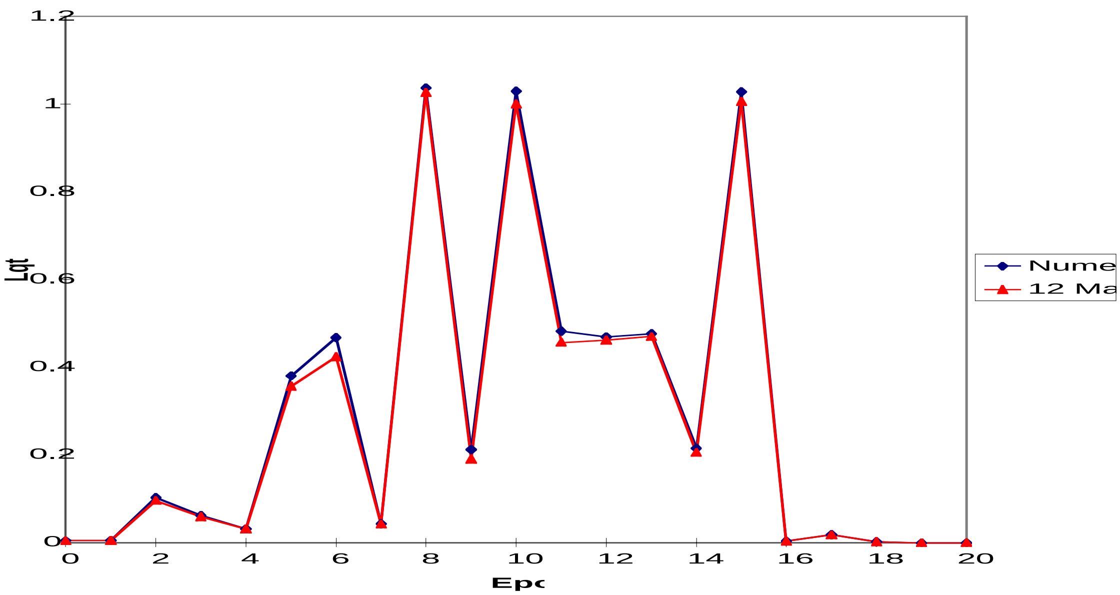
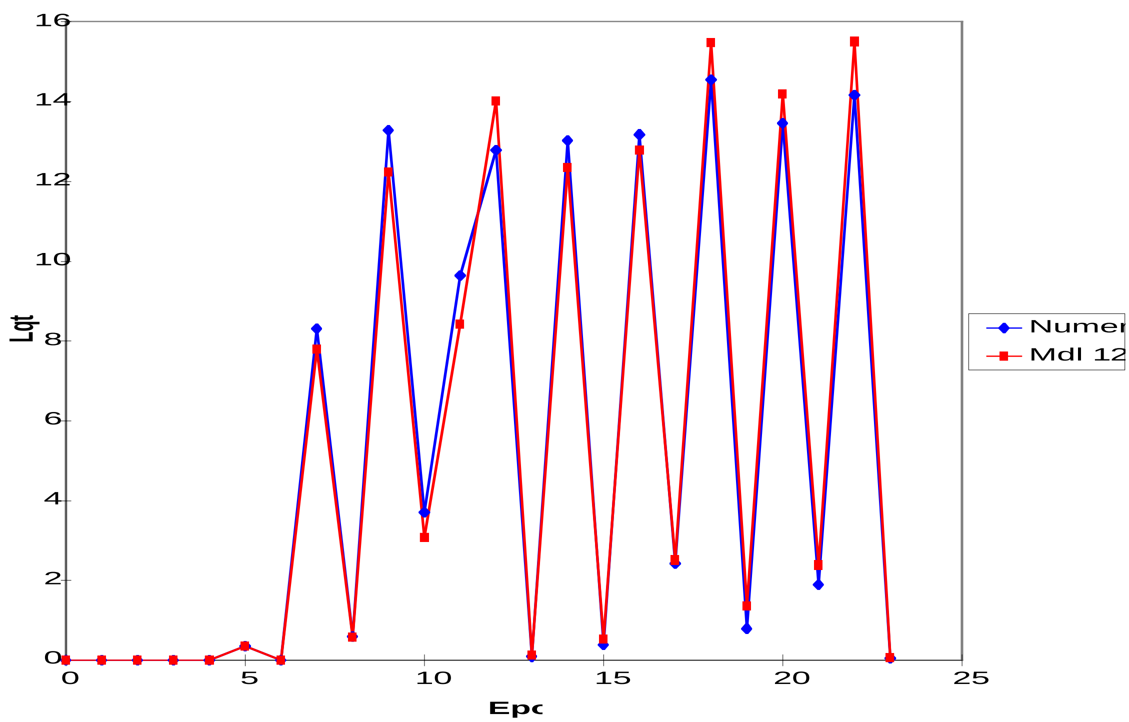


Figure B–4. Taxi-in Queue at ATL



M/M/1 → ../EK/1

The full evolution equations are simpler for this case than for the previous case.

Writing $p(n_1, n_2, t)$ for the probability that the network is in the state (n_1, n_2), and now defining n_1 to be the number of *clients* in the first queue while n_2 is the number of *phases* in the second, we have [15],

$$\dot{p}(0,0,t) = -\lambda p(0,0,t) + k\mu p(0,1,t) \quad \text{[Eq. B-40]}$$

$$\dot{p}(0,n_2,t) = -(\lambda + k\mu)\,p(0,n_2,t) + k\mu p(0,n_2+1,t), 0 < n_2 < k \quad \text{[Eq. B-41]}$$

$$\begin{aligned}\dot{p}(0,n_2,t) = {} & (\lambda + k\mu)\,p(0,n_2,t) + k\mu p(0,n_2+1,t) \\ & + \mu_1 p(1,n_2-k), \qquad n_2 \ ? \ k\end{aligned} \quad \text{[Eq. B-42]}$$

$$\begin{aligned}\dot{p}(n_1,0,t) = {} & -(\lambda + \mu_1)\,p(n_1,0,t) + k\mu p(n_1,1,t) \\ & + \lambda p(n_1-1,0), \qquad n_1 > 0\end{aligned} \quad \text{[Eq. B-43]}$$

$$\begin{aligned}\dot{p}(n_1,n_2,t) = {} & -(\lambda + k\mu + \mu_1)\,p(n_1,n_2,t) \\ & + k\mu p(n_1,n_2+1,t) \\ & + \lambda p(n_1-1,n_2,t), \qquad n_1 > 0; 0 < n_2 < k\end{aligned} \quad \text{[Eq. B-44]}$$

$$\begin{aligned}\dot{p}(n_1,n_2,t) = {} & -(\lambda + k\mu + \mu_1)\,p(n_1,n_2,t) \\ & + k\mu p(n_1,n_2+1,t) \\ & + \mu_1 p(n_1+1,n_2-k,t) \\ & + \lambda p(n_1-1,n_2,t), \qquad n_1 > 0; n_2 \ ? \ k\end{aligned} \quad \text{[Eq. B-45]}$$

The model equations

We begin with the LMINET equations for the departure process [15]. These are

$$\dot{q}_t = \lambda - \mu_t [1 - p_0(q_t, v_t)] \quad \text{[Eq. B-46]}$$

$$\dot{v}_t = \lambda + \mu_t - \mu_t (2q_t + 1)\,p_0(q_t, v_t) \quad \text{[Eq. B-47]}$$

$$o_t = \lambda - \dot{q}_t = \mu_{td} [1 - p_0(q_t, v_t)] \quad \text{[Eq. B-48]}$$

$$\dot{q}_r = o_t - \mu + \mu \frac{k+1}{k+1+2kq_r} \quad \text{[Eq. B-49]}$$

In Equations B-13 and B-14, $p_0(q_t, v_t)$ is given by Equation B-13.

Steady-State Considerations

The steady state of the present case is considerably simpler than that of Section 0. The inter-departure times of the M/M/1 taxi-out queue are exponentially distributed, and independent. Consequently, in steady state the ../Ek/1 runway queue will be a M/Ek/1 queue. For this network, we can assemble familiar steady-state results, to give the exact steady state. Thus, when $\lambda < \mu$ and $\lambda < \mu_t$, in steady state we have [35, pp.53]

$$L_{qt} = \frac{\rho_t^2}{1-\rho_t} \qquad \text{[Eq. B-50]}$$

and also [35, pp.167]

$$L_{qr} = \frac{1}{2}\left(\frac{k+1}{k}\right)\left(\frac{\rho^2}{1-\rho}\right) \qquad \text{[Eq. B-51]}$$

Turning to the model equations, we see that in steady state,

$$q_t = \frac{\rho_t}{1-\rho_t} \qquad \text{[Eq. B-52]}$$

and

$$q_r = \frac{1}{2}\left(\frac{k+1}{k}\right)\left(\frac{\rho}{1-\rho}\right) \qquad \text{[Eq. B-53]}$$

Thus, in the steady state, $\rho_t\, q_t$ and $\rho\, q_r$ from the model equations will give accurate values of L_{qt} and L_{qr}, respectively.

Numerical experiments show that the model equations reach their equilibrium solutions more quickly than does the tandem queue. To compensate for this, we multiplied values of $\rho\, q_r$ from the model equations by the factor $e^{-c\rho^4}$, and chose the constant c for best fit to several cases.

Figures B-5 and B-6 show the agreement between these approximations, and numerical solutions of the full equations, for departures from DTW.

Figure B–5. Comparison of Model Equations and Numerical Solution for Number In Taxi-Out Queue at DTW.

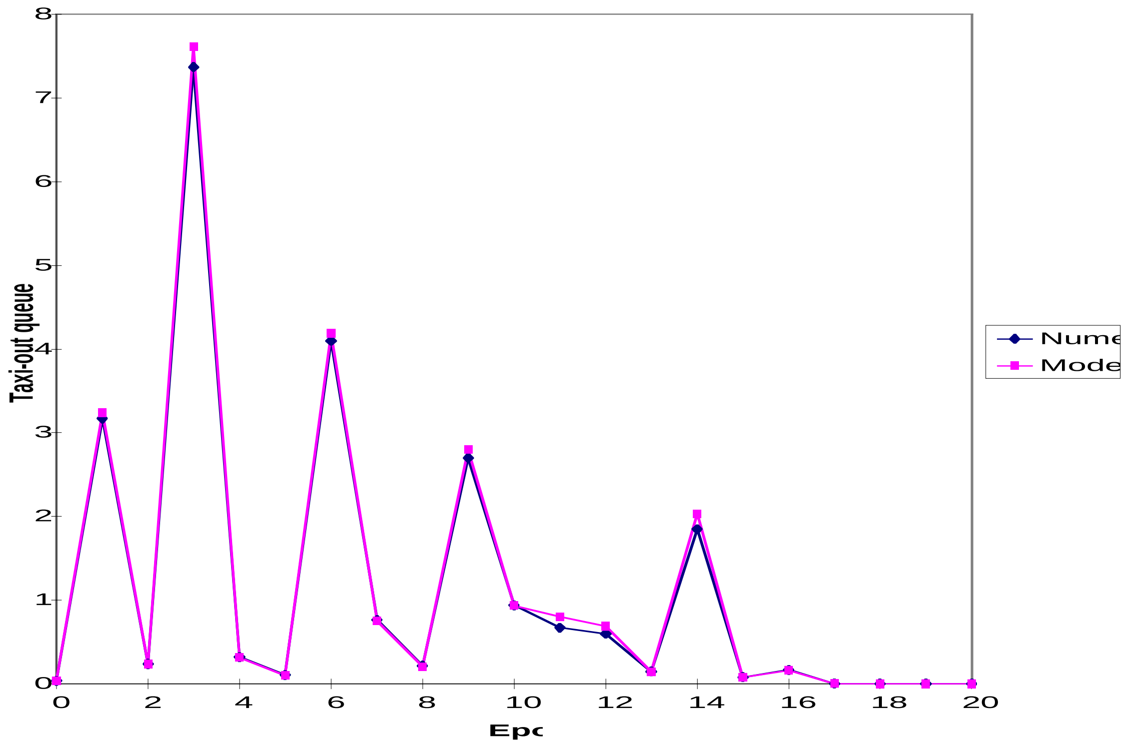
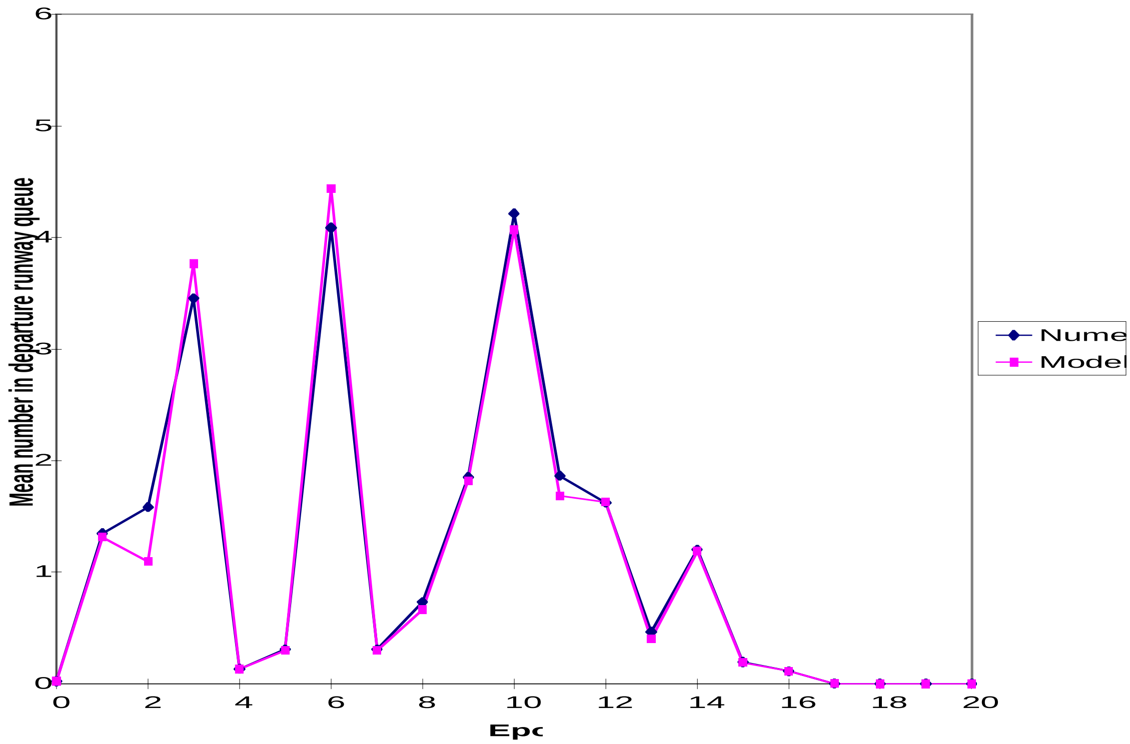


Figure B–6. Comparison of Model Equations and Numerical Solution for Number in Runway Queue at DTW



All the DTW departures had a steady state. To see the model equations at work in cases where demand was strong enough to preclude steady state in some epochs, we used the demand data of Table B-4.

Table B-4. Sample Departure Demands with Some Utilization Rations Larger Than One

Epoch	Demand	Runway capacity	Taxi-out capacity
0	17.76	78.5	87.9464
1	85.80	91.0	87.9464
2	40.44	45.5	87.9464
3	101.04	87.2	87.9464
4	44.88	95.2	87.9464
5	28.68	45.5	87.9464
6	90.24	77.7	87.9464
7	60.00	95.2	87.9464
8	38.04	47.6	87.9464
9	83.28	83.4	87.9464
10	63.96	58.5	87.9464
11	61.20	63.2	87.9464
12	58.44	60.2	87.9464
13	33.00	47.6	87.9464
14	77.76	84.7	87.9464
15	25.68	47.6	87.9464
16	34.80	78.5	87.9464
17	4.80	78.5	87.9464
18	0.00	78.5	87.9464
19	0.00	78.5	87.9464
20	0.00	78.5	87.9464

Figures B-7 and B-8 compare the mean number enqueued in the taxi-out and departure runway queues, respectively.

Figure B–7. Number in Taxi-Out Queue, Example of Table B-3

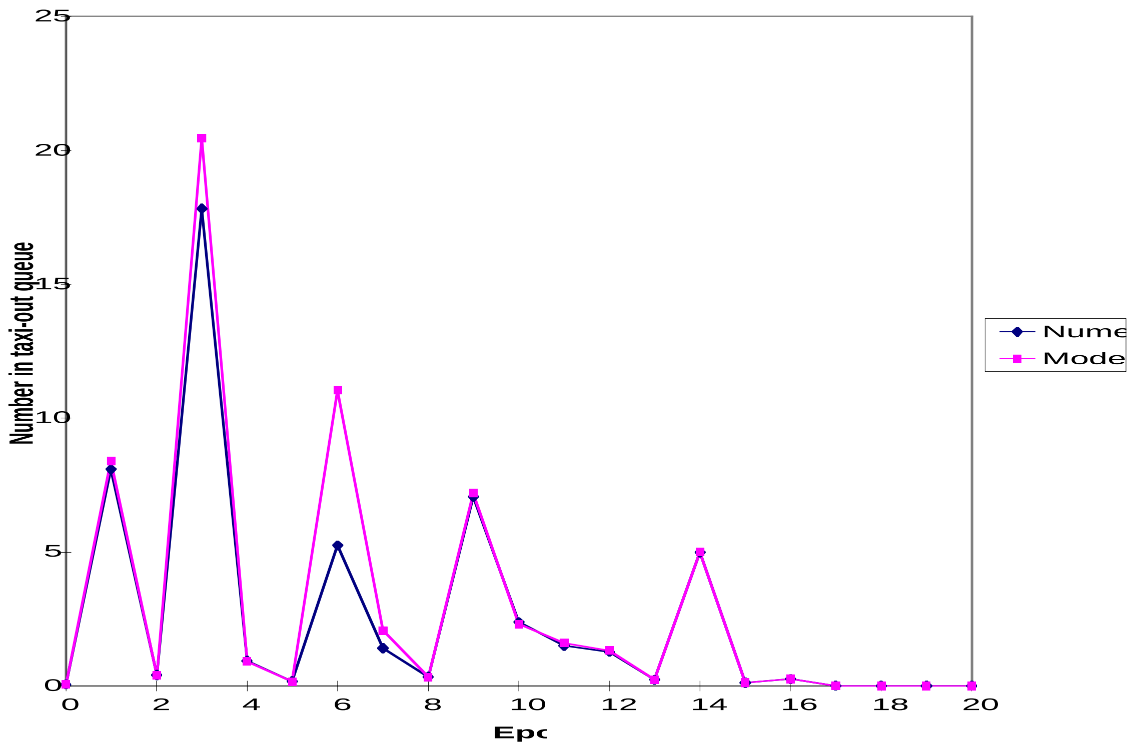
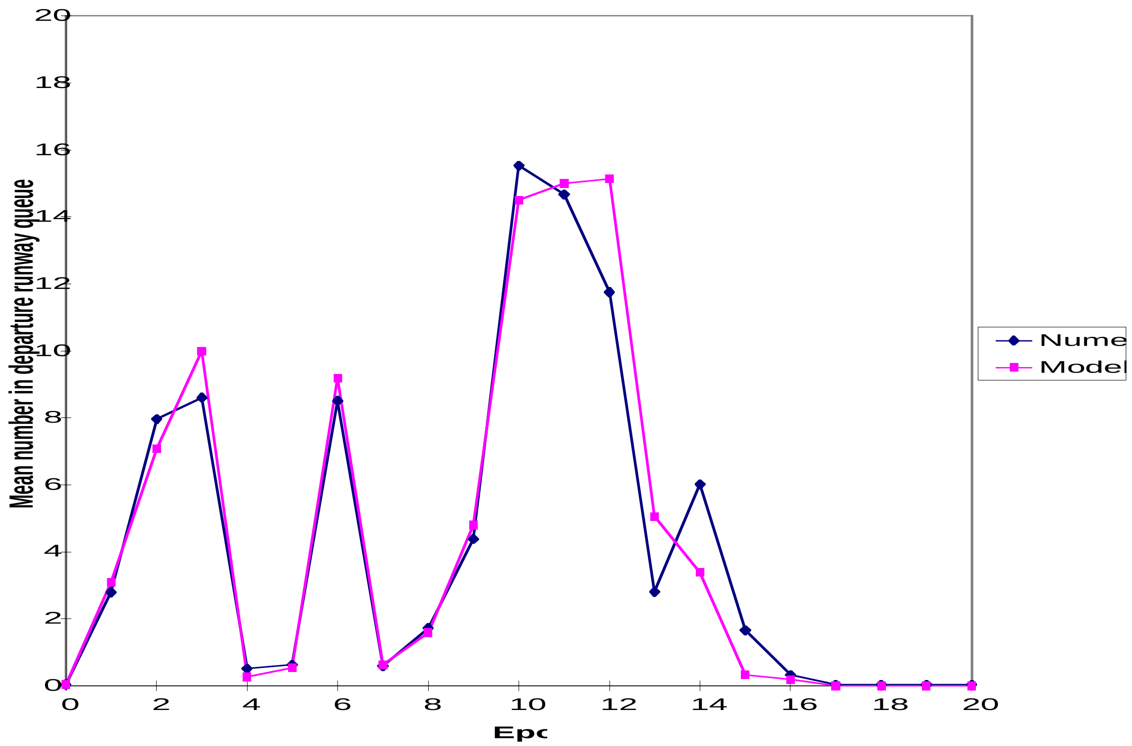


Figure B–8. Number in Departure Runway Queue, Example of Table B-3



SUMMARY

By considering steady-state behavior, we have adapted the LMINET equations for the arrival and departure processes to model more accurately the behavior of a M/Ek/1 queue in tandem with a ../M/1 queue (for arrivals), and a M/M/1 queue in tandem with a ../Ek/1 queue (for departures). We must emphasize again that this work is not an attempt to make rational approximations. Rather, it is an effort to make reasonably accurate model equations that can be solved quickly, for use in preliminary studies. Final results will come from numerical solutions of the full tandem queue equations.